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THE VREDEFORT RING-STRUCTURE OF SOUTH AFRICA

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ABSTRACT

Five theoretical explanations of the marvelous deformation in the Vredefort region, all ascribing it to purely terrestrial forces, are summarized. Two of the hypotheses assume magmatic upthrust to have been the primary cause. A third finds it in tangential force, of the kind represented in orogeny of the ordinary type. The remaining two regard horizontally directed force and magmatic upthrust as both essential, though with differing emphasis on relative importance. These wide contrasts among the five interpretations of the unique "ring-structure" illustrate, of themselves, the difficulty of finding explanation in terms of orthodox geological dynamics. It seems, therefore, advisable to take seriously the published suggestion of Boon and Albritton that the structure may have been developed by the infall of a speedy meteorite of planetoid or asteroid dimensions, followed by readjustments of the scarred and shattered terrain that were induced by the earth's gravitation. The effort to compare reasonable deductions from that double premise with the known facts of the field is described in the second half of the paper.

INTRODUCTION

South Africa is crowded with geological wonders. Not the least startling is the "ring-structure" of the "Vredefort mountain land," crossed by the boundary between the Transvaal and the Orange Free State. Concerning its origin, widely contrasted hypotheses have been published during the last forty years. The last to appear in print is that of B. D. Maree.[1] With the gravimeter he has attempted to complete the map of this structure if it were more fully exposed—that is, after the removal of Karroo sediments which still unconformably cover about one-third of the structure. Studying Maree's report, the present writer, who in 1922 had traversed the area under the expert guidance of A. L. Hall of the Union Geological Survey and of the late G. A. F. Molengraaff, formerly chief geologist of the Transvaal Republic, was led to review also the older views of origin. The gamut of all these opinions is wide and of itself strongly suggests how hard it is to understand the Vredefort structure by appeal to recognized terrestrial forces. Perhaps because of the writer's recent concern with the problem of the lunar "craters," there flashed a question: Does the Vredefort ring-structure represent the deeply eroded remains of a meteorite scar? Soon memory was stirred; it was recalled that J. D. Boon and C. C. Albritton, Jr.,[2] had asked the same question in print, though they did not venture an adequate discussion of it. With the double purpose of advertising the

[1] "The Vredefort Structure as Revealed by a Gravimetric Survey," *Trans. Geol. Soc. So. Africa*, Vol. XLVII (1944), p. 183.

[2] "Meteorite Scars in Ancient Rocks," *Field and Laboratory*, Vol. V (1937), p. 53.

Boon-Albritton idea and also the absence of general satisfaction with the appeals to terrestrial forces as dominant in the structure's development, the following pages have been written. First, the peerless ring-structure itself will be described. There will follow a brief account of the other published views about origin. Finally, the meteorite-scar idea will be somewhat elaborated, in the hope that it may be further examined by those more competent to judge the effects of the infall of a giant bolide (meteorite, asteroid, or planetoid) on the pre-Karroo terrain of the Vredefort region.

THE RING-STRUCTURE

The rocks essentially constituting the Vredefort structure consist of: (1) a thick packet of unfossiliferous quartzites, shales, conglomerates, and interbedded basic lavas—all generally assigned to the late Pre-Cambrian; and (2) "Old Granite" (enclosing some masses of schists), underlying the packet unconformably and now assigned to the early Pre-Cambrian. At some epoch long before the Carboniferous, perhaps as early as the late Pre-Cambrian itself, the amazing deformation of the packet and its granite floor took place. How ever formed, the new structure must have had considerable relief and ruggedness. It was subjected to erosion, more or less continuously, and thus peneplained. In Upper Carboniferous time this peneplain was buried under a relatively thin cover of Karroo sediments, which still remain flat, little warped out of their original attitude. In post-Jurassic time the Karroo cover has been stripped off about two-thirds of the Vredefort ring-structure.

L. T. Nel[3] has made the most complete study of the stratigraphy. From his report and from that of A. L. Hall and G. A. F. Molengraaff[4] Table 1 has been compiled, showing the succession and thicknesses in the stratified mass of the packet, the Pretoria series being at the top.

The stratified beds are seen now to stand at high angles with the horizontal plane, the outcropping edges of the whole "packet" forming a "collar" wrapped about a "core" of Old Granite (see Fig. 1). As exposed, the unconformable contact of core and collar approaches that of a circle 40 kilometers in diameter.

TABLE 1

SUCCESSION AND MEAN THICKNESSES OF THE BEDDED ROCKS

(In Meters)

Pretoria series	3,600
Dolomite series	1,525
Ventersdorp system (basic lavas)	3,700
Upper Witwatersrand division (quartzite, shale [slate], and conglomerate, with diabase sills)	3,900
Lower Witwatersrand division (quartzite, shale [slate], lava beds, with diabase sill)	3,500
Total	16,225

However, according to Maree's gravimetric results (apparently confirmed by data of D. J. Simpson using the magnetometric method of detection)—see L. T. Nel[5]—that contact on the southeast bends out of the circle in such a way that the ground-plan of the core surface is like that of the flat section of a pear which has been sliced longitudinally. Accordingly, Maree puts the

[3] *The Geology of the Country around Vredefort: An Explanation of the Geological Map* (Pretoria: Geological Survey of South Africa, 1927).

[4] *The Vredefort Mountain Land in the Southern Transvaal and the Northern Orange Free State* (separately printed in "Shaler Memorial Series," from *Verhandl. Kon. Akad. Wetenschappen Amsterdam*, Sectie 2, Deel 2 [1928]).

[5] "Remarks in Discussion of Paper by D. W. Bishopp," *Trans. Geol. Soc. So. Africa*, Vol. XLIV (1941), p. xciii.

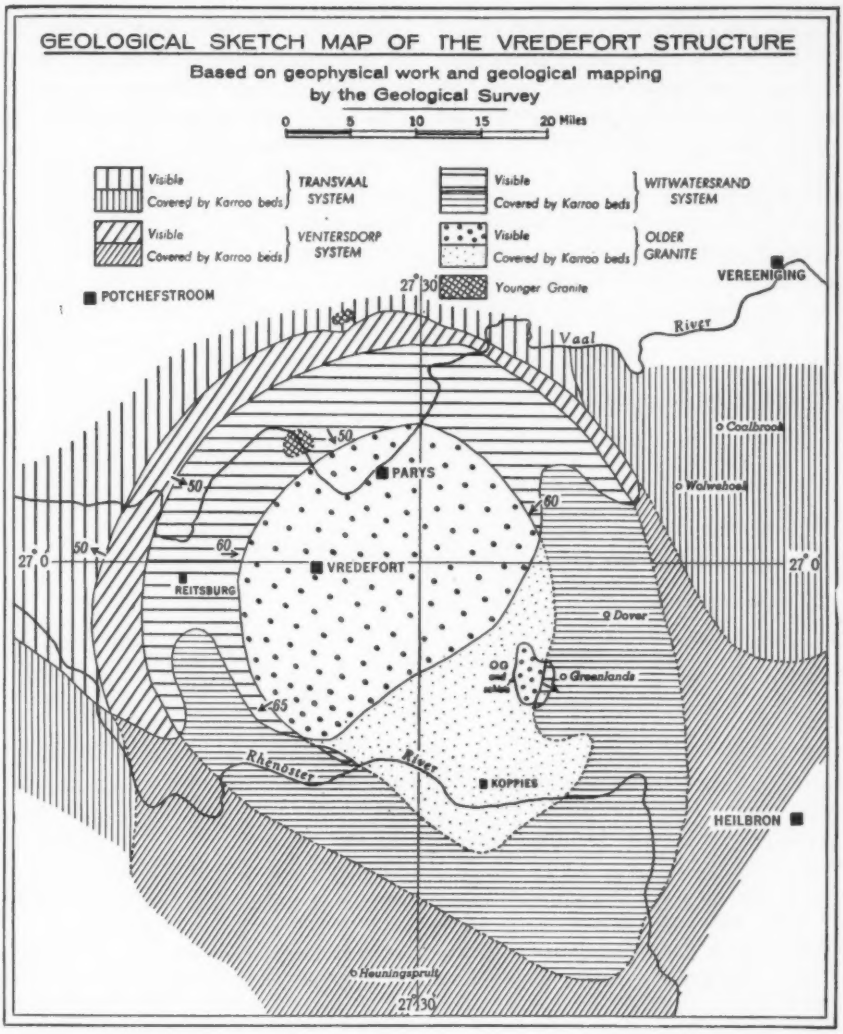

FIG. 1.—Generalized map of the Vredefort region, drawn by L. T. Nel (see ftn. 5) to illustrate the ring-structure and its southeastern extension under the remnant of the Karroo cover, as indicated by the gravimetric method of detection. (Copied by permission of the Geological Society of South Africa.)

maximum, northwest-southeast, diameter of the granitic surface, supposed freed from the Karroo cover, at 50 kilometers.

Along lines radiating out from the center of the granitic area, the collar has outcrop widths ranging from 15 to 20 kilometers.

Nel's large map indicates many observed dips and strikes read within the Witwatersrand divisions. The angles of these dips have been averaged in the three quadrants of the visible structure, mutually separated by the meridian of 27°30′ east longitude and the 27° parallel of south latitude. The averages are shown in Table 2, where the number of readings for each average is given in brackets. Besides vertical dips, those directed in a general way toward the center of the granite core and also those directed in the opposite general direction are separately tabulated.

TABLE 2

SUMMARY OF DIPS (AVERAGES)

	Vertical (1)	Inward (2)	Outward (3)	Grand Average (All Inward) (4)
Northwest quadrant:				
Lower Witwatersrand	[5]	[90] 53°	[8] 60°	[103] 61°
Upper Witwatersrand	.....	[61] 50	[4] 57	[65] 54
Northeast quadrant:				
Lower Witwatersrand	[1]	[33] 55	[4] 65	[38] 62
Upper Witwatersrand	.....	[28] 56	[1] 60	[29] 58
Southwest quadrant:				
Lower Witwatersrand	[1]	[21] 57	[13] 66	[35] 79
Upper Witwatersrand	[1]	[7] 66	[7] 70	[15] 88

The statistics of Table 2 show that in the northerly quadrants the whole of the Witwatersrand system has not only been upturned but also strongly overtilted. The South African geologists seem to agree that the same is the case with the Ventersdorp system. In the Dolomite series on the north, Hall and Molengraaff observed four "inward" dips and regarded them as registering overtilt even at this great distance from the granite core, though those authors gave no direct evidence of such violence of deformation for the Dolomite itself.

From his gravimetric results Maree[6] concludes that, in general, overtilting characterizes the strata only at and near the surface, the dips becoming "outward" at relatively small depth. He does, however, recognize strong overtilting to depth in the northwest quadrant of the ring-structure (see the sections of Fig. 2).

Clearly the stresses set up during this energetic "diastrophism" were enormous, and it is not surprising that Hall and Molengraaff found all the rocks

> to show more or less a cataclastic structure and to be cracked and crushed in many places. The effects of pressure are as a rule concentrated along crush-zones in which they get so strong that the rocks are mylonized or triturated..... The crushing and grinding of the rocks were accompanied by comparatively little [mass-] movement, and although the rocks affected are very rich in cracks and micro-faults, schistose structures are rarely found.[7]

It was to be expected that detailed mapping of the collar would display

[6] P. 191 of ftn. 1.

[7] P. 148 of ftn. 4.

GRAVIMETRIC SURVEY OF THE VREDEFORT DOME
SECTIONS OVER THE STRUCTURE
SECTION A-B

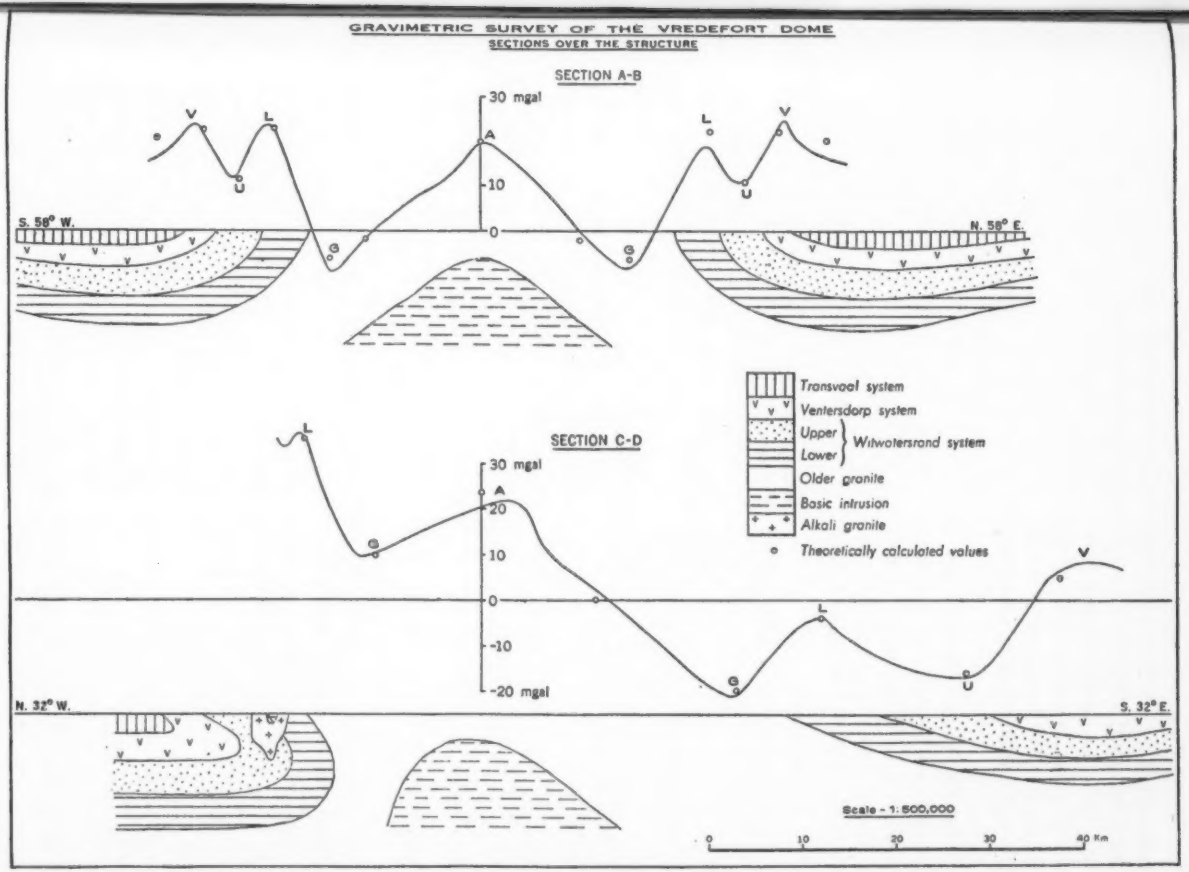

FIG. 2.—Sections from Figure 3 of B. D. Maree's paper, ftn. 1. The lettered curves show the run of gravity anomalies. Those at lettered points were found over outcrops or inferred positions of edges of the various rock systems under the Karroo cover, as follows: *V*—on the Ventersdorp system; *U*—on the Upper Witwatersrand division; *L*—on the Lower Witwatersrand division; *G*—on the Old Granite (core). *A* represents the anomaly above the top of the inferred basic intrusion.

The structure sections, at right angles to each other and with indicated azimuths, are diagrammatic and drawn to illustrate the opinion of Maree that, except in the northwestern quadrant of the ring-structure, the observed inward dips of the collar strata represent only superficial attitudes, the dips in depth being outward. (Copied by permission of the Geological Society of South Africa.)

much macrofaulting; in fact, Nel's map shows many hundreds of observed faults, and there must be many more in belts poor in outcrops. A host of similar dislocations must be represented in depth. The observed faults run in all azimuths on the map.

The intensity of the deformation is further suggested by some of the rapid changes of measured thicknesses of each member of the two Witwatersrand divisions of the collar strata, as these are traced along the curved outcrop. Nel's tables[8] give the ranges of thicknesses. While most of the ranges are of the order expected, because the formations in this thick geosynclinal prism were lenticular from the start, some are not to be so readily explained.

TABLE 3

ILLUSTRATING VARIATION OF THICKNESS

Locality (Farm)	Thickness (In Feet)	Approximate Distance Apart (In Miles)
Procedeerfontein No. 110...	6,000	4
Vaalwal No. 158.....	7,800	14
Koedoesfontein No. 12, etc..	1,300	7
Rooderand No. 26, etc.....	9,000	4
Nooitgedacht No. 56.....	9,700	3
Elandslaagte No. 28.....	9,500	

Concerning the Orange Grove series, Nel wrote:

> Great pressures acting on the group of quartzites and slates have pinched out one or more of the latter in certain localities..... [On account of] the great pressures to which the whole system was subjected in the course of being overtilted and faulted, and so yielded to the stresses set up, ... [the Jeppestown] series in some localities became squeezed out to such an extent that the total thickness may be only 800 feet, instead of the 1,600 feet calculated for the average thickness. This, apart from any lenticular habit the strata may possess, probably accounts for the considerable discrepancies in the thickness of the series here.[9]

A second example is to be suspected in the great differences of thicknesses stated for a composite quartzite-slate member of the Kimberley-Elsburg series (see Table 3).

Such squeezing-out would have been a probable accompaniment of the inevitable stretching of the strata as these were upturned and overtilted.

Incidentally, it may be asked whether the total thickness of the collar strata before their deformation was not greater than the total measured at the existing outcrops.

In spite of all the complications, the average trends of the strikes, like the upstanding ribs of hard quartzite, are eloquent of the fact that the upturning and the overtilting of the beds were controlled by forces directed along lines radiating from a central or subcentral sector of the Old Granite core.

Either after or during the deformation of the strata the collar was invaded by magmatic bodies, whose order of emplacement is given by Nel[10] as follows, beginning with the oldest: (1) basic intrusions (sheets and dikes of gabbro and diabase with subordinate pyroxenite, hyperite, and peridotite); (2) "younger" alkaline-granite stocks; (3) nepheline-syenite dikes and veins; and (4) enstatite-granophyre dikes. Large dikes and sheets of gabbroid rock were injected also into the Old Granite of the core, particularly within a relatively narrow belt along the contact of core and collar.

The younger, alkali-rich, granite occurs in the form of three stocks. Their

[8] Pp. 33, 35, 39, 40, 43, 46 of ftn. 3.

[9] P. 33 of ftn. 3.

[10] P. 60 of ftn. 3.

contacts cut across the strata of the collar in its northern part (see Fig. 3), but at least in one case the Witwatersrand beds seem to have been bulged up so as to form "an irregularly shaped dome or anticline."[11] The nepheline syenites are closely associated in chemistry and time of intrusion with the younger granite. The enstatite-granophyre dikes are highly inclined and cut across the contact between core and collar as well as across the Old Granite well within that contact. Nel agrees with Hall and Molengraaff in taking the view that these peculiar dikes are large-scale injections of the once-vitreous material like, or analogous with, that represented in the countless veins and small irregular masses of pseudo-tachylyte, which S. J. Shand[12] has shown to be local re-melts of the Old Granite.

[11] P. 68 of ftn. 3.

[12] "The Pseudotachylyte of Parijs," *Quart. Jour. Geol. Soc. London*, Vol. LXII (1917), p. 198.

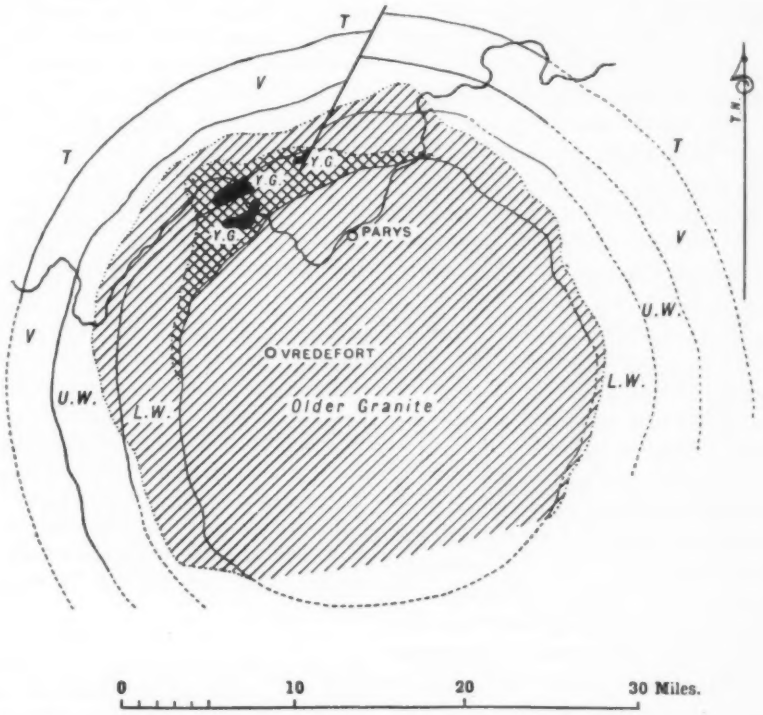

FIG. 3.—L. T. Nel's (see ftn. 3) diagrammatic map of the ring-structure. (Copied by permission of the Geological Society of South Africa.) *T*—Transvaal system; *V*—Ventersdorp system; *U.W.*—Upper Witwatersrand division; *L.W.*—Lower Witwatersrand division; *Y.G.*—younger granite.

The area covered by single-line shading denotes the distribution of metamorphosed rocks and Old Granite, while the portion crosshatched denotes the area of most intensely altered sedimentary rocks.

Broken lines indicate extension of formations under covering of coal measures (Karroo).

The completion of the circle on the south by the broken line is entirely hypothetical, there being no evidence from boreholes that the boundary of the granite is as shown. (The geophysical data of Maree and Simpson were not available in 1927, the year when Nel published this diagram.)

One more principal fact about the collar remains to be mentioned, namely, the advanced thermal metamorphism of the shales and amygdaloidal lavas occurring in the Lower Witwatersrand division and, in the northwest quadrant of the ring-structure, extending into the Upper Witwatersrand division (see Fig. 3). In that region is the locus of the three bodies of younger granite. There, however, the width of the metamorphosed belt is out of all proportion with that expected from the heat and gases of this granite, unless the eruptives coalesce just below the present surface to form a body very much more extensive than all three of the exposed bodies put together. Nel[13] has drawn that inference and actually credits the injection of that greater, largely invisible mass of young-granite magma with being a leading factor in the main deformation at Vredefort.

In its turn the core of Old Granite gives evidence of the energy that must have been expended when the ring-structure was developed. As Hall and Molengraaff noted, this granite "has been subjected to considerable pressure, as shown under the microscope by cataclastic structure. Not seldom the crystals of quartz and feldspar show many cracks filled with a mosaic of crushed material. Nowhere, however, has the pressure given rise to a distinct schistosity."[14] Doubtless connected with that intimate crushing is the widespread macroscopic shattering of the granite, the shatter-blocks being separated or enclosed by the veinlike masses of pseudo-tachylyte. Shand's conclusion that the latter was formed by local re-melting seems to be generally acceptable. The exceedingly fine grain of the pseudo-tachylyte is well explained by A. Holmes[15] as due to the low content of volatile fluxes left in the Old Granite after its own, earlier, crystallization. Assuming that judgment to be sound, one can hardly avoid the deduction of about 700° C. as a minimum temperature for the Old Granite when the partial melting took place. It is clear that the required temperature was not in any large measure the result of shearing of the granite. Heating by pure crustal pressure without plastic flow has been suggested as the cause of the extra heating, but that seems to be a quite inadmissible explanation. Shand left the problem open, though narrowed down to two alternatives. He wrote: "The pseudotachylyte has originated from the granite itself through melting, caused (as I have shown) not by shearing but by shock, or, alternatively, by gas-fluxing."[16]

FIVE THEORIES OF ORIGIN

Five pictures have been painted in print to account for the ring-structure through the operation of purely terrestrial forces. As already remarked, the five hypotheses disagree with one another, and such disagreement among serious and competent workers creates doubt that reliance on the orthodox, textbook principles of geology alone is justified. To illustrate the point best, the five hypothetical pictures will be examined individually.

1. In their book Hall and Molengraaff[17] outlined the various explanations of the ring-structure that were published before 1922. Because those skilled observers made the first detailed map, their theory is the first to deserve attention. They attributed the mighty deformation to two kinds of pressure. The dominant

[13] P. 90 of ftn. 3.

[14] P. 17 of ftn. 4.

[15] See discussion on p. 221 of ftn. 12.

[16] P. 219 of ftn. 12.

[17] See ftn. 4.

kind was horizontal, affecting at least the outer part of the earth's crust as a whole or else over a wide stretch. The other kind of pressure, subordinate but still important, was that causing the vertical upthrust of the core of Old Granite. At the opening of their theoretical argument the two authors presented their vision of what had happened in the Vredefort area as follows:

> In the doubtless very great lapse of time which stretches between the end of the deposition of the sediments of the Transvaal System and the beginning of the deposition of sediments belonging to the Karroo System a peculiar, well localized, and very powerful diastrophism took place in the Vredefort Mountain Land. Consequent on these crust-movements all round a common centre now occupied by the Vredefort [Old] Granite, all the sediments ranging from the base of the Witwatersrand System up to the top of the Transvaal System were tilted and largely overtilted. In the centre of the disturbed area the Vredefort Granite was uptruded to a level which, before it was lowered again by denudation, certainly must have been much higher than that occupied by the uppermost sediments of the Transvaal System. The result, as it can be seen now, is a boss of granite, the Vredefort granite-boss encircled by a girdle of tilted and overtilted sediments. The total vertical displacement of the granite in the central portion of the Vredefort dome may be estimated as more than 14,000 m.
>
> The granite was uptruded at the same time that the strata of the sediments were tilted and finally overtilted. What is the relation between these two phenomena? Has the granite played an active role in the process of updoming, or has it been moved upwards passively, following the uplift of the sedimentary roof?[18]

The hypothesis that the updoming was caused primarily by the upward push of a large body of deep-seated magma on the plug or core of Old Granite was considered and rejected as quite inadequate. Less mental trouble is encountered if one assumes that the primary cause of the updoming was an orogenetic one and that centripetal stresses in the earth's crust caused the horizontal strata and with them the underlying floor of granite and schists to be elevated and arched up into a huge circular dome. If one admits the plane of application of the centripetal forces to have been lower than the present visible surface of the granite, an overtilted position of the strata in the lowermost portion of the slope of the dome could be expected. Further, the intense stress, the effects of which are visible in all the rocks throughout the Vredefort area, is, on this assumption, of necessity the result of the powerful pressure which resulted in the updoming of a huge block of the earth's crust.

> The magma in the depth below the central granite was released by the local relief of pressure due to the updoming, and got the opportunity to invade with force the much heated and probably semiplastic granite floor as well as the roof of the dome. Differences in the capacity to which the various roof strata were able to resist pressure would give the ascending magma during the updoming an opportunity to be injected as sills.[19]

On pages 162–63 of their book is a summary of the final hypothesis put forward by Hall and Molengraaff:

> The present structure of the Vredefort Mountain Land is based on centripetal pressure as the major cause, associated with a "point" uplift as a minor cause and dependent upon the emplacement of a younger magma. The combined effect is the updoming of the central granite as a more or less passive body. . . . . As regards the time order, the authors consider that the centripetal pressure came into force first, to be followed later on by movements of magma.

Hall and Molengraaff knew well the toughness of the genetic problem. They pointed out that "the initial cause of the centripetal pressure in the earth's crust remains unexplained."[20] They could find no good reason why the ring-structure should have been developed in the midst of a great geosynclinal prism of sediments. Although their cross section of the

[18] Pp. 144–45 of ftn. 4.

[19] P. 155 of ftn. 4.

[20] P. 163 of ftn. 4.

ring-structure (Fig. 1 of their book) is diagrammatic, it seems to indicate a central uplift of at least 30 kilometers and therefore a departure from isostatic balance very much greater than any yet demonstrated in the existing earth.

In view of all these deficiencies the Hall-Molengraaff hypothesis can hardly be accepted as a sound explanation for the extraordinary features of the ring-structure.

2. Toward the end of his book Nel agreed that the nature of the forces that resulted in the "updoming of the rock formations" is "imperfectly understood." He wrote:

> The Vredefort structure may be due either to magmatic upheaval or to centripetal pressure. . . . . Future investigations and research may throw more light on this subject. Data may be collected which will indicate which of the two, horizontal compression or magmatic upheaval, was the chief agent which actually produced the updoming. At present it appears that the two were really closely associated.[21]

He had a degree of skepticism about the idea of centripetal movements of the rocks under converging pressures. On page 109 we read:

> Now tangential forces generally tend to produce elongated upheavals or anticlinal structures, and it may be difficult to picture, therefore, just how a round and practically symmetrical structure like the Vredefort occurrence could be formed, unless the horizontal compression was very evenly distributed. The existence of evenly distributed radial pressures, however, would be most unusual.

On the other hand, Nel emphasizes magmatic upheaval and suggests that the magma concerned was that of the younger alkali-rich granite, extended underground as a "batholith" which was about as wide as the visible surface of the Old Granite core. He assumes that the upthrust would cause the pronounced overturning, eversion, of the sedimentary beds overlying the Old Granite.

The reasons for making this last assumption need clarification. Furthermore, the validity of the magmatic hypothesis must be questioned until it be coupled with a satisfactory theory of origin for the "batholith" itself and for the assumption that it would have had the urge to rise so high into the earth's crust in spite of the great weight of Old Granite and its sedimentary cover. In other words, Nel did not succeed in removing the objections against the double "postulate" of Hall and Molengraaff.

3. B. D. Maree[22] reverses the emphasis and thinks that the deformation was due to centripetal, "tangential," pressure of the kind referred to in theories of ordinary orogeny, magmatic invasion of the earth's crust being unessential to the upturning and overtilting of the sedimentary beds. He makes a valiant attempt to explain the assumed convergence of the "tangential" pressures toward the center of the ring-structure, but the corresponding argument is so charged with uncertain assumptions that the result is far from convincing. The new gravimetric evidence that the ring-structure is pear-shaped, rather than circular, in ground-plan seems overstressed, and Maree's suggestion that successive pressures, applied at two different assumed epochs, would have sufficient centripetal quality appears doubtful.

Maree accounts for the magmatic intrusions into the ring-structure (supposed complete before this invasion) by appeal to "isostatic inequilibrium," induced by the major deformation. He also leaves unsolved this problem of the origin of the magma, which he assumes "because of isostatic considerations" to have "segre-

[21] P. 108 of ftn. 3.

[22] See ftn. 1.

gated into basic and acid phases." Few petrologists would be willing to guess how such segregation could have been accomplished under the given conditions. Even if it did take place, it is hard to follow the reasoning embodied in the following passage in Maree's paper:

> It is noteworthy for isostatic considerations that the magma segregated into basic and acid phases and that the lighter acid alkali-granite was injected into the heavy sediments where there was a relative surplus of mass, and the heavy basic gabbro was injected into the light Older granite where there was a relative deficiency of mass. . . . . Thus, the isostatic equilibrium was adjusted by the segregation and migration through replacement of material, with the result that the whole Vredefort structure and the [surrounding] geosynclinal basin are to-day in relatively good isostatic equilibrium.[23]

4. In complete opposition to Maree's opinion, E. B. Bailey[24] concluded that "a hypothesis of magmatic upheaval and concomitant centrifugal pressure seems much more applicable at Vredefort than one of centripetal pressure."[25] After referring to the difficulty which Hall and Molengraaff felt in accounting for the overtilt of the collar strata, Bailey remarked:

> It may, however, be pointed out that it is impossible to communicate an upward push through a plastic column without at the same time developing a centrifugal push. If the upward push raises the overlying rocks, the outward push (at any fixed point) will steadily increase. It will also produce outward deformation, if this deformation can be accommodated by being indirectly communicated upwards so as to find relief in the raising of the roof. Subterranean outward deformation will laterally extend the superficial dome and ameliorate its slopes.[26]

Bailey attributes the upthrust at Vredefort to the "younger magma" of Hall and Molengraaff.

To support his view of the matter, Bailey drew a parallel with the deformation of schists and sedimentary beds by upthrust of the Arran granite boss in Scotland, but in the section illustrating the Arran "parallel" none of the beds is shown as overtilted and dipping toward the intruded granite. Corroboration for Bailey's idea about Vredefort is not obvious from either the section or the accompanying text.

If it be assumed that the "younger magma" under the Vredefort area pushed up the Old Granite and its sedimentary cover to form a dome with central height of, say, 15 kilometers, it would be conceivable that the collapse of the dome under its own weight might have given the strata "inward" dips, but it seems incredible that the angles of these dips would be as low as those observed at the existing surface of erosion. Then, too, Bailey's hypothesis can hardly be generally accepted until some reasons are adduced for the localization of the magmatic invasion and for the enormous upthrusting power assumed for it. Neither of those reasons is given or to be readily suggested by even prolonged consideration of the problem.

5. D. W. Bishopp[27] also rejected the postulate of centripetally directed pressure as playing an important role and tried to find the essential solution in magmatic upthrust of the core of Old Granite. He wrote:

> The dynamics of the structure appear to be fairly simple in general principle. A minor uplift in the bottom of the primary shallow basin [the broad geosynclinal prism of which our "collar" sediments formed a part filled this

[23] P. 196 of ftn. 1.

[24] "Domes in Scotland and South Africa: Arran and Vredefort," *Geol. Mag.*, Vol. LXIII (1926), p. 481.

[25] P. 484 of ftn. 24.

[26] P. 483 of ftn. 24.

[27] "Geodynamics of the Vredefort Dome," *Trans. Geol. Soc. So. Africa*, Vol. XLIV (1941), p. 1.

basin] seems to have been associated with high temperatures from a local underlying magma. . . . . An upward pressure from this magma, which need not have been excessively high, first placed the apex of the minor uplift under tension, and caused its rupture with the extrusion of plasticized material into and through it. The process continued, and the sediments were still further upturned and thrust apart.

The upward pressure of the magma on the lower portion of the basin now brought another set of forces into play. The upward swing of the inclined and rather rigid sediments forming the flanks of the structure created a toggle-action, and induced immense longitudinal compression in them, many times greater than the thrust of the magma generating it. As a result the fractured ends of the sediments were still further uplifted and overturned, and the plastic Old granite between them was constricted and squeezed, its uplift being further intensified thereby. There the process ended, from the structural point of view.[28]

Like Bailey, Bishopp does not explain why the magmatic body was developed and located under the Vredefort area or why it had the assumed power of upthrust. The published argument is weakened by these gaps in reasoning, which the present writer finds to involve an apparent inconsistency. Bishopp assumes the Old Granite plug to have been plasticized,[29] and yet, when invoking "toggle-action" as the condition for the centrifugal pressure supposed to cause the strong upturning and overtilting of the sedimentary beds, he assumes a high degree of strength for the same granite when under much greater (horizontal and centrifugal) stress. Further, it is not easy to see how the toggle principle can apply at all after the bared top of the granite plug has reached a horizontal diameter exceeding 5 or 10 kilometers.

The foregoing sketch of five hypotheses erected to account for the Vredefort ring-structure proves the great diversity of opinions about the nature of the deforming forces. The corresponding kinds of pressure may be summarily described as in Table 4.

Hall and Molengraaff and also Nel leave open the question as to the cause of the horizontal pressure. All three realized the difficulty of imagining how such pressure could become centripetal. Maree referred it definitely to the crustal condition assumed in the ruling theory of orogeny—this kind of pressure being here with some arbitrariness called "tangential." His success in showing how it became centripetal with reference to the Vredefort granite core has been found highly doubtful.

With the exception of Maree, all the authors assume as vital the upward magmatic pressure on the visible core of Old Granite, but none of them suggests a cause for the development of the big magmatic body under the Vredefort area or a reason for the assumed gigantic displacing energy of the body. There can be no doubt about the upthrust of the Old Granite core, for at the existing surface of erosion its top is on a level with the Pretoria series of beds outside the ring-structure; but to suppose that an underlying magmatic mass had within itself a great upthrusting power is manifestly hard to believe. On the other hand, the meteorite-scar hypothesis, soon to be described, seems competent to account for the localization of the upthrusting, deep-lying magma on a big scale, this magma having been pushed up, passively, during an isostatic adjustment of pressures still farther down in the earth. The meteorite-scar hypothesis, like those of Bailey and Bishopp, emphasizes centrifugal pressure as the cause of overtilting of strata but is not troubled by the necessity of proving that the magmatic upthrusting pressure could be resolved into strong, centrif-

[28] P. 16 of ftn. 27.

[29] Pp. 7, 10, and 15 of ftn. 27.

ugal, horizontally directed pressure as is the case with each of the Bailey and Bishopp hypotheses.

Hall, Molengraaff, Nel, Maree, and Bailey postulate updoming on a scale unmatched in any other known crustal structure, so far as the height of the dome is concerned. Bishopp postulates upturning without doming in anything like the same amplitude. It will be seen that the meteorite-scar hypothesis postulates deep basining at the surface, with concomitant upturning and ultimate overtilting of the sedimentary beds of the collar.

TABLE 4

Authors	Kinds of Pressure Assumed	
Hall and Molengraaff	Horizontal and centripetal	Magmatic and vertical
Nel	Horizontal and centripetal(?)	Magmatic and vertical
Maree	"Tangential" and centripetal	.....
Bailey	.....	Magmatic, vertical, and derived centrifugal (collapse of "dome")
Bishopp	.....	Magmatic, vertical, and derived centrifugal (toggle-action)

DOES THE VREDEFORT STRUCTURE REPRESENT A METEORITE SCAR?

When, in 1937, Boon and Albritton asked that question, they shared the sense of the lack of collective security felt by geologists in general concerning any published solution of the Vredefort problem—a lack not likely to be supplied by the more recent, contradictory suggestions of Bishopp and Maree—and also recognized the truth of a principle phrased by Shand: "When one is dealing with an extraordinary phenomenon, no possibility is too extraordinary to be worthy of consideration."[30] Boon and Albritton developed the idea that some crustal structures (including a few which had been called "cryptovolcanic") in North America may be the scarring effects of infalls of massive meteorites millions of years ago and then applied the idea to the Vredefort ring-structure. They wrote: "Impact and explosion of a gigantic meteorite could account for the salient structural features of the Vredefort area."[31] Such an infall would explain: (1) the transverse and oblique faults around the margins of the core, (2) the absence of volcanic materials, and (3) the evidence of "unprecedented pressures" and the intense crushing of the rocks of what are here called core and collar.[32] They described their suggestion with extreme brevity. For that reason and also because the suggestion was published in a journal not widely known to the geological and geophysical professions, it has not received the attention it deserves.[33]

Absolute proof that the Vredefort deformation resulted from impact is manifestly impossible. The erosion of probably much more than two hundred million years has utterly destroyed the original relief of the ring-structure and may be expected to have removed all remnants of the assumed meteorite. Hence some direct evidences of infall, such as are given at craters recently formed on the earth, are not to be had.

[30] P. 217 of ftn. 12.

[31] P. 63 of ftn. 2.

[32] P. 64 of ftn. 2.

[33] The present writer is doubtful of one conclusion of Boon and Albritton, namely, that the compressional waves sent horizontally into flat-lying strata from the locus of meteoritic impact should be, as it were, stereotyped in the form of concentric anticlinal and synclinal folds in those beds.

The discussion of a supposed parallel at Vredefort must therefore be theoretical and fearsomely difficult. Reasoning must be partly on the principle of analogy, which cannot be easily guaranteed as true homology, and partly by theoretical deductions, which in the nature of the case cannot be thoroughly verified by experiments. Yet, in the writer's opinion, both analogies and theoretical considerations tend to breed tolerance for the conception that celestial forces, rather than terrestrial forces, were dominant in the development of the ring-structure.

TABLE 5

CRATERS DEFINITELY RECOGNIZED AS DUE TO METEORITIC INFALLS

LOCALITY	APPROXIMATE DIAMETER (M.)	PRESENT DEPTH BELOW RIM (M.)	OBSERVED DIPS (GENERALLY OUTWARD) OF STRATA IN RIM		EVIDENCE OF HIGH TEMPERATURE DEVELOPED BY IMPACT
			Average	Range	
Canyon Diablo, Arizona	1,200	175	30°	0°–90°+	Silica glass
Odessa, Texas	170	5	.....	20 –90 +	.....
Brenham, Kansas	15	3	.....	.....	.....
Campo del Cielo, Argentina (one of many)	53	5	.....	.....	Silica glass
Henbury, Australia (one of many)	220×120	15	.....	.....	Silica glass
Boxhole, Australia	175	16	.....	.....	.....
Dalgaranga, Australia	70	5	.....	.....	.....
Wabar, Arabia (one of several)	100	12	.....	.....	Silica glass
Wabar, Arabia	55	.....	.....	.....	Volatilization of both SiO_2 and iron
Ösel, Estonia (one of six)	100	17	45°	28 –85	.....
Ösel, Estonia	50	3+	.....	35 –50	.....
Ösel, Estonia	55×35	3+	.....	.....	.....
Siberia (one out of ten or more)	50	.....	.....	.....	.....

F. G. Watson[34] has listed more than a score of pits made in the earth's crust by infall of (chiefly iron) meteorites, the collisions having been so recent that these craters are still more or less intact. From that list and from data supplied in the corresponding descriptive papers Table 5 has been compiled.

The craters named in Table 5 were wholly or in large part formed by pure percussion, as in the cases represented by rain pits in mud and pits made by speedy balls, bullets, or dud shells in deep clay. That any of these listed craters was much deepened and widened by gaseous explosion is uncertain. L. J. Spencer[35] has found evidence of the volatilization of both silica and nickel-iron at one of the Wabar craters, and special investigation may prove other instances. But the explosive energy of such volatilized materials escapes estimation. Professor H. N. Russell in a letter to D. M. Barringer, Jr.,[36] suggested the likelihood of another kind of gaseous explosion resulting from the fall of large stones and irons at high velocity. Each of these pushes ahead of it a "wad" of greatly compressed air, endowed with explosive power sufficient to

[34] *Between the Planets* (Philadelphia: Blakiston, 1941), p. 139.

[35] "Meteorite Craters as Topographical Features of the Earth's Surface," *Smithsonian Rept. for 1933*, p. 307 (reprinted from *Geog. Jour.*, Vol. LXXXI [March 1933] pp. 227–42).

[36] *Meteor Crater in Northern Central Arizona* (paper read before the National Academy of Sciences, Nov. 16, 1909; privately printed), p. 22.

drive out much rock debris and thus form a crater.

At each of the three craters named in Table 6 the mass of the (unitary) meteorite and its depth of penetration are known. With that information the velocities of impact can be roughly estimated by making two assumptions: first, that each meteorite was a sphere; second, that Poncelet's formula[37] showing the relation between velocity and depth of penetration for spherical bullets applies in all three cases. Neither of these assumptions can be regarded as correct, but with them a general idea of the respective velocities can be obtained. The results of the calculation are given in column 8 of Table 6. Although the "constants" appearing in the Poncelet formula were determined empirically for bullets fired into the different terrains at the relatively low velocities of cannon fire, it is probable that the computed velocities are higher than those with which the three meteorites struck the ground. That the actual velocities of impact were indeed low is a conclusion readily accepted when allowance is made for the braking effect of the atmosphere on missiles of these small dimensions.

TABLE 6

CALCULATED IMPACT VELOCITIES OF THREE METEORITES

Locality and Reference	Nature of Meteorite	Mass of Meteorite (Kg.)	Radius of Meteorite, Assumed Spherical (M.)	Terrane Struck	Diameter of Crater (M.)	Depth of Penetration (M.)	Computed Velocity at Impact (Km/Sec)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Henbury, Australia (p. 161 of ftn. 34)	Iron	200	0.14	Sandstone, slate, etc.	9	3	2.5+
Paragould, Arkansas (p. 322 of ftn. 35)	Stone	375	0.30	Clayey soil	7	2.5	0.8
Knyahinya, Hungary*	Stone	300	0.27	Clayey soil	1.5	3.5	2.0

* G. P. Merrill, "The Meteor Crater of Canyon Diablo, Arizona; Its History, Origin, and Associated Meteoric Irons," *Smithsonian Misc. Coll.*, Vol. L (1908), p. 491.

[37] See C. Cranz, *Lehrbuch der Ballistik* (5th ed.; J. Springer, Berlin: 1925), Vol. I, p. 489.

D. M. Barringer[38] and colleagues estimated the mass of the Canyon Diablo missile as equal to that of a sphere about 400 feet in diameter. A meteorite of that size and density would strike the ground with a large fraction of the velocity it had when entering the atmosphere. This would be, at minimum, about 10 km/sec. The kinetic energy at impact would therefore be so great that much volatilization of nickel-iron and sandstone would appear inevitable. However, none of the many observers at Canyon Diablo has reported evidence of such volatilization, though the sandstone is clearly shown to have been melted by the heat of collision. In view of all the facts, Barringer[39] concluded that the Canyon Diablo crater was excavated by a swarm of meteoritic irons, great in total mass but so spread out that air resistance reduced the impact velocity well below 10 km/sec. Accordingly, this investigator assigned the excavation of the crater to pure percussion, explosion by volatilized meteorite or rock being practically ruled out.

While some of the kinetic energy was

[38] "Meteor Crater in Northern Central Arizona" (address delivered before the Harvard Club of Boston, Oct. 13, 1926 [typewritten copy]), p. 17.

[39] P. 20 of ftn. 36.

used up in heating, even melting, meteorite and rock, a greater part was employed in excavating, ejection, of debris. Still another fraction was responsible for the remarkably thorough pulverization of a vast quantity of the invaded sandstone. Similar "rock flour" or "rock powder" was developed in the small Henbury and Estonian craters.

At the front of the Canyon Diablo meteorite or swarm of meteorites the pressure must have reached many hundreds of thousands of atmospheres. Under that pressure the particles of the rock powder were, according to a principle established experimentally, shot into the invaded strata horizontally outward and also upward, thus furnishing enough properly directed pressure to deform the strata.[40] In this way the sandstone and limestone were upturned to form a large part of the rim of the Canyon Diablo crater. There the upturning was differential, so that in two places the strata are now vertical. At one point B. C. Tilghman[41] recorded overtilting by about 10° beyond the vertical.

At the largest Estonian crater the beds of the invaded dolomite show maximum upturning at nearly 85°.[42] In a personal letter to the present writer, Dr. M. K. Hubbert describes actual overtilting of the caliche (surface calcareous layer) in the rim of the rim of the Odessa (Texas) meteor crater.

As we now turn attention specifically to the problem of the Vredefort ring-structure, we note at once that, if this does represent a meteorite scar, we have to deal with orders of magnitudes much higher than those that characterized the phenomena at Canyon Diablo. There, as at Vredefort, the terrain struck was a series of nearly horizontal sedimentary rocks. According to the analogy, therefore, the Vredefort strata should have been upturned at average angle much steeper than that found at Canyon Diablo; the crushing and shattering should have been still more intense; volatilization of meteorite and rock should have produced much larger volumes of gas and correspondingly greater effect on the final shaping of the crater. All these effects would be drastic, whether the meteorite were stony or of the nickel-iron class; for simplicity in the following discussion the denser kind of material will be assumed.

On the other hand, the analogies derived from all the recently formed craters are of comparatively little help in accounting for several important features of the Vredefort structure, namely: (1) the remarkable degree of overtilting of the collar strata, (2) the upthrust of the Old Granite core through a vertical distance of something like 15 kilometers, and (3) the intense metamorphism of the Witwatersrand sediments making the broad belt which stretches through the northwest and northeast quadrants of the ring-structure.

Thus the differences between the Arizona and South African structures are both qualitative and quantitative. To understand those differences on the basis of the impact hypothesis, it is necessary to make a number of pure assumptions, the choice of which represents a case of "seasoning to taste," with all that that means in causing mental unease. The procedure is not new. Every one of the other published suggestions as to the origin of the Vredefort ring-structure is

[40] P. 489 of ftn. 37; and also C. Cranz in "Ballistische Kraterbildung," *Gerlands Beitr. zur Geophysik*, Vol. XVII (1927), p. 389.

[41] "Coon Butte, Arizona," *Proc. Acad. Sci. Philadelphia*, Vol. LVII (1905), p. 887.

[42] See W. Kranz, "Krater von Sall auf Ösel, wahrscheinlich 'Meteorcrater,' " *Gerlands Beitr. zur Geophysik*, Vol. LI (1937), p. 50.

similarly based on a hypothesis *ad hoc*. Each rests on unsecured premises essential in the argument. Each has been found wanting. Is it not, then, advisable to give the sixth—impact—hypothesis a hearing, even though absolute proof of its truth is now and in the indefinitely distant future quite improbable? The practical question is: Can the Boon-Albritton idea best explain the phenomena at Vredefort and at the same time avoid the difficulties felt with the five competing hypotheses, all of which regard purely terrestrial forces as responsible for the ring-structure?

Let us continue to be bold and use the Canyon Diablo case as a rough guide in a preliminary test of the impact hypothesis when applied to the African structure. To make the comparison concrete, we shall for the moment, arbitrarily, think of the Arizona meteorite as a nickel-iron sphere with diameter of 100 meters (giving nearly the mass deduced by Barringer and colleagues) and velocity of impact at 10 km/sec (perhaps five times the velocity the "swarm" might have had). The diameter of the Arizona crater, before any slumping enlarged it, was about 1,100 meters; the depth of penetration of the meteorite was here about 400 meters.

At Vredefort the diameter of the assumed crater must have exceeded 50,000 meters; the depth of penetration must have been of the order of 15,000 meters, the bottom of the pad of sediments pushed down ahead of the infallen body reaching 10,000 or more meters still deeper into the earth's crust. The minimum impact velocity may be placed at about 10 km/sec; it may have been two to four or more times greater. Let this meteorite be supposed spherical, composed of nickel-iron, and having initial diameter taken to be, alternatively, 5,000, 10,000, and 20,000 meters.[43]

The ratios of the kinetic energy possessed by the Vredefort sphere to that possessed by the Canyon Diablo sphere would range between 125,000 (5,000-meter sphere striking at 10 km/sec) and 128,000,000 (20,000-meter sphere striking at 40 km/sec). Correspondingly, the pressure at the front of the Vredefort missile would range from nearly 3,000,000 atmospheres to about 55,000,000 atmospheres (as calculated from an equation supplied by Boon and Albritton).[44]

The impact momenta of the assumed 5,000-meter, 10,000-meter, and 20,000-meter spheres at Vredefort would have been, respectively, 125,000, 1,000,000, and 8,000,000 times that of the 100-meter meteorite at Canyon Diablo with the same impact velocity of 10 km/sec. All three ratios would be larger (with maximum at 32,000,000) in proportion with increase of impact velocity in each of the three Vredefort cases. And again we note that at Canyon Diablo the missile was probably a swarm, with much smaller impact velocity and impact momentum than a spherical body of the same tonnage would have.

The ratios of kinetic energies, frontal pressures, and momenta are so large that it does not seem wild to think that the imagined crater at Vredefort had width and depth as great as those deduced from the ring-structure and from the thickness of the sedimentary formations.

[43] Professor Francis Birch has suggested the possibility that this sphere might have been fragmented by impact with air and rock. If so, impact velocity and kinetic energy and impact momentum would all be a little smaller than as stated in the text. Such differences would, however, not be vital in the argument founded on the comparison with the Canyon Diablo case.

[44] "The Impact of Large Meteorites," *Field and Laboratory*, Vol. VI (1938), p. 59.

In one important respect, however, the Canyon Diablo crater could not be homologous with that at Vredefort. Because of the relatively low impact velocity at Canyon Diablo, neither meteorite nor invaded rock was volatilized to a discernible extent; hence there the crater must have been formed by pure percussion. If the impact velocity at Vredefort was anywhere between 10 and 40 km/sec, there must have been volatilization on a big scale and that only a few seconds after the instant of initial impact. Boon and Albritton[45] argue that this volatilization was largely concentrated in the pad of sediments pushed down by the speedy meteorite. In any case it would seem inevitable that the excavation of the Vredefort crater, if of meteoritic origin, was caused by gaseous explosion as well as by the pure percussion of solid meeting solid.

The part played by pure percussion has already been indicated in the case of the Arizona deformation. The gigantic pressure, communicated through the pulverized material of the pad ahead of the Vredefort meteorite, would drive much of this matter into the annulus of rock surrounding the crustal sector directly struck by the huge visitor from space. Therewith the strata of the annulus would be tilted up on all sides, the average angle of tilt, produced by this action alone, being much higher than the average at Canyon Diablo.

With much diffidence the writer will now enter on a brief discussion of that tough problem—the cause or causes for the overtilting of the collar strata. The reader is warned beforehand that no very definite conclusion will be reached; any treatment has to be deductive and deduction is bound to be suspect where sound premises are so few and the phenomenon is outside the range of controlled experimentation.

There is some reason to doubt that gaseous explosion alone would have caused important overtilting. The major explosions at Monte Somma and Krakatoa seem not to have brought about even upturning of the old layers of lava and ash. Neither were the chalk beds uptilted by the powerful explosion of 1916 at the mine crater of La Boiselle, France.[46]

On the other hand, the interval of time separating complete penetration of the imagined meteorite at Vredefort and the gaseous explosion could not have exceeded a few seconds. Is it not possible, therefore, that in this case upturning of the strata was the joint product of both percussion and gaseous explosion? At Canyon Diablo there was strong upturning by pure percussion, apparently unaccompanied by gaseous explosion.[47] At Vredefort the conditions would have been different. Is it possible that there the collar strata were, during and immediately after their violent upturning, overthrown by the enormous "centrifugal" pressure of the expanding gas of explosion?

A second cause of the overtilting at Vredefort is perhaps worthy of consideration. It is suggested by the fact that, after the strong upturning of the collar strata, the Old Granite core was pushed up about 15 kilometers, so that its surface now stands at the same level as the Pretoria beds outside the disturbed annulus. In the attempt to understand

[45] P. 63 of ftn. 44.

[46] P. 307 of ftn. 39.

[47] One of G. K. Gilbert's photographs (see his 1895 Presidential Address to the Geological Society of Washington, p. 20 of pamphlet; reprinted in *Science*, Vol. III [New Ser., 1896], pp. 1–13) seems to show that, when a clay ball was dropped on a flat surface of clay, the layers of this invaded clay were overturned.

this fact more speculation may be ventured.

For reasons given in many books and papers the writer believes it wise to assume that the earth has been cooling since its birth. He also favors the idea that, until recent geological time, our planet has had a true crust, resting on a layer—substratum—of eruptible, vitreous basalt. As a corollary he assumes that, when the Vredefort structure was formed, the earth's crust was thinner than in Tertiary time, hundreds of millions of years later, and had a correspondingly steeper thermal gradient. Being hotter and therefore weaker as well as thinner, the crust at the earlier date was specially prone to yield under isostatic pressure. It seems highly probable that the crust sector struck by the assumed meteorite would have been somewhat weakened by shattering. The impact hypothesis implies that a great load was taken off that sector by the colossal explosion, the area of unloading having a minimum diameter of perhaps 60 kilometers. The question arises as to whether the unloaded sector should have yielded to the unbalanced pressure on the substratum basalt, so that this magma rose, pushing upward the granite core. The question can be rephrased: Assuming such isostatic adjustment, can we best explain both the origin of the deep-seated magmatic body (postulated by some of the competing theories about the Vredefort structure) and the upthrust of the Old Granite overlying that magma? A definitive answer is out of the question, but the line of speculation here suggested seems to ease understanding of the emplacement of thick injections of liquid basalt into the granite core, the injections being regarded as apophysal from the large body of liquid in depth. Perhaps, too, the gravity and magnetic anomalies found by Maree and Simpson have the signs and magnitudes expected if, under the ring-structure, the crust has at the present time an extra thickness of frozen basalt matching the mass of the substratum liquid that had risen into the wounded crust.[48]

If, as supposed, the gaseous explosion left a crater with central depth of something like 15 kilometers and a diameter of about 70 kilometers, the deeper, unwounded part of the sial ("granitic" layer of the earth's crust), endowed with some strength, would be bent upward differentially—most at the central axis of the core and least near the outer limit of the collar. When equilibrium was finally attained, after this regional isostatic adjustment, the collar strata might be expected to be strongly overtilted.

Such overtilting would be additional to any produced by the initial impact and would also be a function of the amount of initial upturning. It seems reasonable to think that, because the penetration by the meteorite was progressive, this upturning was most pronounced in the younger strata of the collar, which, therefore, were carried farthest from the vertical.

A third conceivable cause for the overtilting, based on the volume elasticity of the sediments and Old Granite, can be valued only by the trained elastician. He too will be troubled by uncertainties as to the velocity of penetration by the meteorite and as to the velocities of the

[48] The foregoing explanation of the upthrust of the core granite is, of course, quite unlike that of Nel's (see p. 90 of ftn. 3): that the required pressure was supplied, directly or indirectly, by the younger granite when in the magmatic condition.

It may here be remarked that in the opinion of the present writer the origin of the younger granite and associated nepheline-syenite dikes and veins must still be regarded as a mystery.

shock wave in sediments and Old Granite. He will be dealing with mighty forces of compression and restitution—forces directed both vertically and horizontally. The vertical force of restitution would have been differential, causing maximum upward rebound at the center of the crater. The horizontal force of restitution would also have been differential, with maximum along a level at or near the contact of sediments and Old Granite. Is it possible that the elastician, in spite of the elusiveness of this problem, might give assurance that the play of purely elastic forces set up by impact should have participated to some extent in the overtilting?[49]

One other outstanding feature of the Vredefort structure remains on our list of tests for the impact hypothesis, namely, the intense thermal metamorphism of the Witwatersrand strata in the collar. Figure 3 shows how widespread are its effects on the northwestern half of the ring. We recall, too, Nel's explanation of this differential effect in terms of a supposed wide extension of the younger granite magma, at shallow depth, under both collar and core. Another possibility seems worth consideration. The data of Table 2 show that overtilting of the collar strata is at maximum in the northwest quadrant of the ring-structure. Maree's section (Fig. 2 of the present paper) indicates a minimum of overtilting in the southeast quadrant. Thus, field observations suggest that, if the impact hypothesis is correct, the meteorite did not fall vertically but plunged downward at an angle with the horizontal plane less than 90°, toward the north-northwest. On that side the pressure of impact and also plastic deformation of the collar strata, especially those of the Witwatersrand divisions, would be at maximum. In consequence, these sediments would have been specially heated. Their temperature before the deformation averaged probably as much as 350° C., and it would perhaps be doubled by the heat of impact. Considering the fact that the sediments then carried relatively high percentages of connate water, their thorough recrystallization would be inevitable. That the temperature of the Witwatersrand sediments was high even before the invasion by the younger granite is apparent from Nel's[50] observation that thin apophyses of that granite were not chilled by contact with the sediments.

Special heating of the northwest quadrant of the ring-structure is further suggested by the relatively great abundance of the pseudo-tachylyte in the Old Granite of that quadrant, as indicated in Nel's large map.[51]

CONCLUSIONS

It is clear that the testing of the impact hypothesis when applied to the Vredefort ring-structure is like "making bricks without straw." As in so many geological problems, essential data are hidden in the depths of both time and space. At Vredefort the initial topography, with all its significant details, has been swept away; vital conditions for an objective solution of the structural problem were in depths forever invisible and unreachable. It is a case

[49] Perhaps the inward dips of the collar strata might have been locally increased when thick masses of these rocks, loosened by shattering, slid down with some rotation into the deep crater before this cavity was filled by upthrust of the core granite.

[50] Pp. 69 and 86 of ftn. 3.

[51] Is the asymmetry of the Vredefort collar homologous with that of the vast rim of the lunar Mare Imbrium, the serrate lunar Apennines corresponding to the chaotic pile of upturned rock and rock fragments which may be expected to have been formed at the front of the obliquely falling meteorite at Vredefort?

where deduction from uncertain premises, far outrunning induction from observations in the field, represents the only mode of attack; hence, no one who looks fairly at the meager facts in hand can be expected to have fixed faith in the impact idea. Why, then, labor over it? The answer is multiple. First, the idea should be retained until the resources of the geophysical laboratory have been used for relevant and well-designed experimentation. Second, geologists, the world over, may well follow the lead of Boon and Albritton in the search for more structures which can be reasonably attributed to pre-Recent infalls of giant meteorites; if found, comparison of the respective terranes may conceivably add to the data for Vredefort. Third, the impact hypothesis should be retained because it does seem competent to account best for: (*a*) the spectacular displacement of rock and corresponding colossal energy expended at Vredefort, (*b*) the intensity of the crushing of the collar rocks, (*c*) the shattering of the core granite, (*d*) the upturning of the collar strata, (*e*) the contrast of the structural elements in the northwest and southeast quadrants of the ring-structure, (*f*) the upthrust of the core, (*g*) the injections of gabbroid magma, (*h*) the differential metamorphism of the Witwatersrand sediments, and (*i*) probably the origin of pseudo-tachylyte. In addition, the impact hypothesis has two negative advantages: It does not involve the doming of the Vredefort terrane on an incredible scale, and it does not assume great intrinsic power of upthrust for any deep-seated, isolated body of magma, though the ability of magma to transmit pressure of extraneous origin is held most accountable for the rise of the Old Granite core.

On the other hand, the writer's general argument is affected by some major uncertainties. The chief of these relates to the mechanism suggested for the overtilting of the collar strata. In that mechanism we have imagined the possible co-operation of the initial force of impact, the forces at work during isostatic adjustment, and the elastic forces of restitution. Hardly less disturbing is the question as to whether the collar strata could keep the observed degree of continuity if the short-lived forces of the first and third kind were important in the overtilting. The first and third difficulties call for guidance by the expert elastician. The second calls for relevant laboratory experiments, using models with properly reduced dimensions, such as those recommended by M. K. Hubbert.[52] In this connection it may be noted that E. Öpik, the eminent astronomer, has made appropriate computation and found that in relation to the energy of a massive meteorite, comparable with one of the smaller asteroids, rock matter should behave almost as if it were a true liquid.[53] Evidently, then, the value of the meteorite-scar idea in the Vredefort problem is not to be judged fairly unless due attention is paid to relations and principles quite different from those usually emphasized in theories of crustal deformation.[54]

[52] "Theory of Scale Models as Applied to the Study of Geologic Structures," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), p. 1505.

[53] See "Researches on the Physical Theory of Meteor Phenomena, I. Theory of the Formation of Meteor Craters," *Pub. Observatoire Astron. Université de Tartu (Dorpat)*, Vol. XXVIII (1936), p. 1.

[54] The temporary "craters" in water, milk, and glycerin, made by infalling solid spheres and cinematicographically photographed by A. M. Worthington and R. S. Cole ("Impact with a Liquid Surface, Studied by Aid of Instantaneous Photography," *Phil. Trans. Roy. Soc. London*, Ser. A, Vol. CLXXXIX [1897], p. 137, and Vol. CXCIV [1900], p. 175) are suggestively like the imagined crater at Vredefort.

THE PROBLEM OF THE LIPALIAN INTERVAL[1]

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ABSTRACT

Occasionally sweeping generalizations cling in the literature which are not supported by detailed studies by recent workers. The present paper, based largely upon a study of the literature, is an attempt to draw a coherent picture from the many conflicting statements concerning the pre-Cambrian–Cambrian succession.

It is tentatively concluded that many sediments now classed as Lower Cambrian may have been deposited in pre-Cambrian time, resulting in transition from pre-Cambrian to Cambrian sediments with little or no break in deposition. Evidence is also presented to show that the acquirement of the shell-forming habit may have taken place in a comparatively short time and that this time may be represented by continuous marine deposition.

DEFINITION OF TERMS

The extensively used term "Lipalian" was coined by Charles D. Walcott, who defined it as "the era of unknown marine sedimentation between the adjustment of pelagic life to littoral conditions and the appearance of the Lower Cambrian fauna. It represents the period between the formation of the Algonkian continents and the earliest encroachment of the Lower Cambrian sea."[2]

Walcott accepted W. K. Brooks's hypothesis of the origin of life, and, in order to explain the sudden appearance of the highly evolved Cambrian fauna, he postulated marine deposition only in areas which have never been exposed to observation. The unfossiliferous sedimentary formations which apparently do not long antedate known Cambrian formations were considered by Walcott to be of continental origin. Walcott specifically stated that the long Lipalian interval is "represented by deposition of the great series of pre-Cambrian sedimentary rocks on the North American continent."[3]

An entirely different concept from that expressed by the term "Lipalian interval" is that of the pre-Cambrian (Ep-Algonkian) unconformity. Concerning this unconformity, Walcott wrote, "I have completed my study of the relation of the Cambrian and pre-Cambrian in North America and have concluded that the pre-Cambrian unconformity is universal in all known localities of Cambrian sedimentation and that the depressions were epicontinental, mainly nonmarine, and in no way connected with the subsequent Cambrian sedimentation."[4]

The two concepts, even though in part expressed in the same paper, are not entirely compatible. They should not be considered synonymous. They may not, and in many cases do not, coincide in duration of time or in geologic implication. Walcott has pointed out the presence of sediments of continental origin in Lipalian time, in which case the pre-

[1] A preliminary report of this problem was read before the geology section of the Tennessee Academy of Science, Nashville, November 29, 1946.

[2] "Cambrian Geology and Paleontology," *Smithsonian Misc. Coll.*, Vol. LVII (1914), p. 14. The term "Lipalian" was proposed in a paper presented in 1910 but not published until 1914.

[3] "The Cambrian Faunas of China," *Carnegie Inst. Wash. Pub. No. 54*, Vol. III (1913), p. 29.

[4] P. 31 of ftn. 3.

Cambrian unconformity would be between Lipalian sediments and Cambrian sediments and might represent only a small fraction of Lipalian time.

THE PRE-CAMBRIAN UNCONFORMITY

Geologists have long considered the Lower Cambrian to be separated from the pre-Cambrian by a widespread and profound unconformity. However, restudy of Lower Cambrian sections by recent workers suggests that, in some cases, the unconformity may not be the boundary between pre-Cambrian and Lower Cambrian sediments.

The problem presents a twofold aspect. One phase concerns the classification as Lower Cambrian of excessive thicknesses of sediments conformably underlying formations bearing Lower Cambrian fossils; the other phase concerns the relationship of recognized pre-Cambrian formations to the overlying "Lower" Cambrian formations.

The concept of a universal unconformity at the base of the Lower Cambrian was strengthened by the stratigraphic practice of extending the Lower Cambrian downward from the lowermost fossiliferous formation until a marked unconformity was encountered. A few writers have suggested that these thick unfossiliferous formations may in part be pre-Cambrian. More recently, the National Research Council Committee on Cambrian Stratigraphy has followed the practice of placing the base of the Cambrian at the base of the lowermost fossiliferous formation.[5]

Lower Cambrian sediments and a possible transition from pre-Cambrian to Lower Cambrian rocks can be expected in two areas in North America—the Cordilleran trough and the Appalachian trough.[6]

THE CORDILLERAN TROUGH

In the Cordilleran trough recognized pre-Cambrian igneous, metamorphic, and sedimentary rocks may be directly overlain by Lower, Middle, or Upper Cambrian formations, indicating that the unconformity did not have the same time value everywhere in the trough. In many parts of the area the lowermost fossiliferous formation is conformably underlain by considerable thicknesses of quartzite of which the base may be concealed. In the Nopah–Resting Springs, California section reported by J. C. Hazzard[7] the unfossiliferous formations underlying the zone bearing the Obolella fauna are over 8,000 feet in thickness, more than the entire fossiliferous Lower, Middle, and Upper Cambrian. The committee on Cambrian stratigraphy[8] has since placed the base of the Cambrian 4,000 feet above Hazzard's boundary, thereby classifying approximately 4,000 feet of the basal unfossiliferous sediments as Lower Cambrian.

In the northern part of the trough C. F. Deiss has restudied the classic Cambrian sections of British Columbia and Alberta. The work of Deiss[9] indicates a considerable thickness of unfossiliferous sediments (except for Scolithus, etc.) below the Olenellus zone. In the Nevada area extensive studies by H. E.

[5] "Correlation of the Cambrian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), pp. 993–1003.

[6] Keweenawan formations of the Lake Superior region, which are pre–Upper Cambrian and which may include sediments deposited in Lower and Middle Cambrian time, are not considered here.

[7] "Paleozoic Section in the Nopah and Resting Springs Mountains, Inyo, California," *Calif. Jour. Mines and Geol.*, Vol. XXXIII, No. 4 (1937), pp. 273–339.

[8] P. 996 of ftn. 5.

[9] "Cambrian Formations of Southwestern Alberta and Southeastern British Columbia," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 951–1026.

Wheeler[10] on the basal Cambrian indicate great thicknesses of quartzite below the lowermost fossiliferous formation. Wheeler classifies this thick unfossiliferous formation as "Lower Cambrian and pre-Cambrian(?)"[11] and very ably criticizes the practice of considering it necessary to extend the base of the Cambrian downward until a marked unconformity is encountered.

The studies by Deiss indicate that a marked angular unconformity exists in the Montana area; but to the northward, in Alberta, much less of the Beltian has been removed by erosion and the two series are generally conformable.[12] In another paper Deiss states, "In the Bow Valley area [Alberta] every known exposure of Cambrian–pre-Cambrian contact exhibits the basal pebbly Cambrian

TABLE 1

CORDILLERAN CLASSIFICATIONS

HAZZARD NOPAH RANGE 1937	DEISS PTARMIGAN PEAK 1939	WHEELER PIOCHE DISTRICT 1943	CAMBRIAN COMMITTEE, 1944 NOPAH RANGE
WOOD CANYON FM. 3033'	MT. WHYTE FM. 275'	PIOCHE SHALE 600'	WOOD CANYON FM.
STIRLING QUARTZITE 2593'	ST. PIRAN SS. 815'	PROSPECT MT. QUARTZITE, 2,000'	STIRLING QUARTZITE
* ? JOHNNIE FM. 2550'	FORT MOUNTAIN 865'	BASE UNKNOWN	
NOONDAY DOLOMITE 1500'	UPPER BELTIAN SHALE		
PRE-CAMBRIAN			

* POSSIBLE UNCONFORMITY
HEAVY LINE INDICATES BASE OF CAMBRIAN

Recent interpretation also suggests that, contrary to the traditionally accepted view, the unconformity separating the pre-Cambrian from formations now classed as Lower Cambrian is in places neither marked nor profound and may even indicate only minor disconformity.

[10] "Lower and Middle Cambrian Stratigraphy in the Great Basin Area," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 1781–1822.

[11] P. 1809 of ftn. 10.

sandstone resting almost conformably on the slightly eroded surface of the Hector shale."[13]

N. E. A. Hinds, who has devoted considerable study to the pre-Cambrian–Cambrian contact of the western United States, states that the Beltian sediments

[12] Pp. 1011–12 of ftn. 9.

[13] "Lower and Middle Cambrian Stratigraphy of Southwestern Alberta and Southeastern British Columbia," *Bull. Geol. Soc. Amer.*, Vol. LI (1940), p. 768.

are largely marine and so similar to Early Paleozoic formations that he considers the Algonkian a Paleozoic period.[14] Classifying the Beltian series as Paleozoic would meet with the disapproval of many geologists, including the writer. However, Hinds's studies, together with those of Deiss and others, are significant in indicating the absence in places of a marked break between pre-Cambrian and Cambrian formations.

THE APPALACHIAN TROUGH

Lower Cambrian sediments in parts of the Appalachian trough reveal a situation quite similar to that existing in the Great Basin area of the Cordilleran trough. The classification of the thick unfossiliferous Ocoee and Chilhowee groups has long been a problem.

Arthur Keith[15] mapped (from the base upward) the Snowbird, Hiwassee, and Cochran formations as the Unicoi group, which is the equivalent of James Safford's[16] Ocoee. The Nichols, Nebo, and Murray formations composed the Hampton group according to Keith and with the overlying Hesse or Erwin quartzite were the equivalent of Safford's Chilhowee. Keith placed the base of the Cambrian at the base of the Unicoi. United States Geological Survey practice[17] follows Keith in including the Unicoi in the Cambrian but disagrees with Keith by including both the Cochran and Hesse formations in the Chilhowee group. Charles Schuchert[18] placed the base of the Cambrian at the base of the Hampton group, thereby including all the Unicoi group in the pre-Cambrian.

C. E. Resser considered the problem in several papers and in one paper[19] placed the base of the Cambrian at the base of the Hesse quartzite, classified the Unicoi and Hampton groups as Beltian, and referred the Beltian to the Paleozoic.

The committee on Cambrian stratigraphy[20] placed the base of the Cambrian at the base of the lowermost fossiliferous formation, the Hesse quartzite, and included the underlying formations in the pre-Cambrian.

P. B. King, H. W. Ferguson, L. C. Craig, and John Rodgers,[21] in a detailed stratigraphic study of the formations of northeastern Tennessee, consider the Unicoi, Hampton, and Erwin formations as forming the basal clastic group of Lower Cambrian age. They state that the basal clastic beds range from 4,000 feet to over 7,500 feet in thickness and assign (at Butt Mountain, Tennessee, where the thickest section is given) approximately 1,100 feet to the Erwin formation.[22] They classify the entire group as Lower Cambrian because "the basal clastic group is a conformable sequence which is overlain conformably by the Shady dolomite and rests unconformably on the pre-Cambrian igneous and metamorphic rocks. No fossils except the worm tube, *Scolithus*, have been ob-

[14] "Late Pre-Cambrian Rocks of Western North America," *Pan-Amer. Geol.*, Vol. LXXI (1939), pp. 44–46.

[15] *U.S. Geol. Surv. Folio 143* (1907).

[16] *The Geology of Tennessee* (Nashville: S. C. Mercer, 1869).

[17] "Lexicon of Geologic Names of the United States," *U.S. Geol. Surv. Bull. 896* (1938).

[18] *Stratigraphy of the Eastern and Central United States* (New York: John Wiley & Sons, 1943), pp. 301–8.

[19] "Cambrian System (Restricted) of the Southern Appalachians," *Geol. Soc. Amer. Spec. Paper 15* (1938), p. 2.

[20] Chart I of ftn. 5.

[21] "Geology and Manganese Deposits of Northeastern Tennessee," *Tenn. Div. Geol. Bull. 52* (1944).

[22] Fig. 5 of ftn. 21.

served in the basal clastic group in northeastern Tennessee. Elsewhere the Erwin and its equivalents contain a few fossils of Lower Cambrian age (Butts, 1940, p. 40). As the Hampton and Unicoi are conformable with the Erwin and consist of similar rocks, and as *Scolithus*, like that in the Erwin, occurs as low as the top of the Unicoi, the whole group is probably of Lower Cambrian age."[23]

TABLE 2

APPALACHIAN CLASSIFICATIONS

SAFFORD 1869	KEITH 1907	U.S.G.S. 1937	RESSER 1938	SCHUCHERT 1943	KING, ET AL 1944	CAMBRIAN COMMITTEE 1944
	HESSE	HESSE	ERWIN	HESSE	ERWIN	ERWIN
CHILHOWEE	HAMPTON: MURRAY	CHILHOWEE: MURRAY	BELTIAN: HAMPTON	MURRAY	BASAL CLASTICS: HAMPTON	PRE-CAMBRIAN
	HAMPTON: NEBO	CHILHOWEE: NEBO	BELTIAN: HAMPTON	NEBO	BASAL CLASTICS: HAMPTON	
	HAMPTON: NICHOLS	CHILHOWEE: NICHOLS	BELTIAN: HAMPTON	NICHOLS	BASAL CLASTICS: HAMPTON	
	UNICOI: COCHRAN	CHILHOWEE: COCHRAN	BELTIAN: UNICOI	COCHRAN	BASAL CLASTICS: UNICOI	
OCOEE	UNICOI: HIWASSEE	UNICOI: HIWASSEE	BELTIAN: UNICOI	HIWASSEE	BASAL CLASTICS: UNICOI	
	UNICOI: SNOWBIRD	UNICOI: SNOWBIRD	BELTIAN: UNICOI	SNOWBIRD	BASAL CLASTICS: UNICOI	
	IGNEOUS & METAMORPHIC	IGNEOUS & METAMORPHIC				

HEAVY LINE INDICATES BASE OF CAMBRIAN

At many places in the northern Appalachians the nature of the pre-Cambrian–Lower Cambrian contact has not been determined. Frequently, Lower Cambrian formations are marked by an overthrust at the base; in other places the contact is buried. Concerning the situation in western Vermont, C. E. Resser and B. F. Howell state that "most of the strata . . . . are referred to the Lower Cambrian, but in the absence of fossils, definite correlations are not possible. Some of these strata are lithologically similar to, and may represent parts of the pre-Cambrian."[24]

THE LIPALIAN INTERVAL

The sudden appearance of fossils at the beginning of Cambrian time has long been considered one of the most striking aspects of geologic history. So firmly entrenched is the belief in the slowness of evolution that many writers consider the Lipalian period to have extended far back into the pre-Cambrian. The general opinion is well expressed by Charles Schuchert and Carl O. Dunbar who state, "The suddenness of the appearance of armor in several phyla may be more apparent than real, for the Lipalian interval is one of the greatest breaks in the geologic record and probably represents many tens of millions of years dur-

[23] P. 29 of ftn. 22.

[24] "Lower Cambrian Olenellus Zone of the Appalachians," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), p. 202.

ing which the evolution of shells was taking place."[25]

The writer believes that evidence presented by the fossils themselves, both in the Lower Cambrian and in later periods, suggests that the period of development of shells was far shorter than is generally believed and was represented by continuous marine deposition.

Two lines of evidence will be considered, namely, the first appearance and the evolution of new forms since the Lower Cambrian and the nature of the Lower Cambrian fauna.

Evolution, when considered in relation to geologic time, has on numerous occasions proceeded with phenomenal swiftness. The first appearance of every new group of fossils is a "sudden" appearance. Unheralded "first appearances" include *Graptozoa* in the Upper Cambrian and *Bryozoa* in the Ordovician. Many other groups could be added to the list. For such groups there is no evidence of a long period during which the shell-forming habit was acquired. On the other hand, there is no doubt that a long period of evolution and development took place prior to their first appearance as fossils. The ability to form a protective covering was acquired during a time when marine deposition was continuously taking place. There is no more necessity for believing that marine deposition was not taking place for some time immediately preceding the appearance of the Lower Cambrian fauna than there is for believing that deposition was not taking place for some time prior to the first appearance of graptolites or bryozoans or other groups.

The ability to form a protective covering may be regarded as an additional characteristic acquired by an already highly evolved organism. Examples are not rare in which an organism has apparently quickly adopted a characteristic which has markedly changed its life habits. The change from a water habitat to a land habitat is such an instance; the change in locomotive habits of reptiles is another. Still further evidence is presented by the rapid evolutionary history of such groups as ammonites in the Jurassic, reptiles in the Triassic, *Graptoloidea* in the Ordovician, and others. The changes become evident only when comparative forms are well preserved as fossils.

Concerning the fauna of the Lower Cambrian, P. E. Raymond[26] points out that the fauna of the Lower Cambrian numbers only about four hundred and fifty-five species, and, although organisms may be highly evolved, the fauna is "simple"[27] compared to that of later periods. The first fauna of the Lower Cambrian reveals an even greater simplicity. Mason[28] states that in the lowermost fauna, the Nevadia zone, only two species are known. Mason's work also shows that the Nevadia fauna, so far, has been described from only one locality—the Palmetto Range (Barrell Spring) section.

When considering the fauna preserved, it is important to consider the nature of the sediments and the chances of preservation of the record. In the Appalachian trough the Nevadia zone is not known although shaly members of formations preceding the Olenellus zone are considered suitable for preservation. Concerning the lower unfossiliferous formations

[25] *Historical Geology* (New York: John Wiley & Sons, 1941), p. 147.

[26] *Prehistoric Life* (Cambridge: Harvard University Press, 1939), p. 23.

[27] P. 28 of ftn. 26.

[28] "Cambrian Faunal Succession in Nevada and California," *Jour. Paleon.*, Vol. XII (1938), pp. 287–94.

of Alabama, Charles Butts writes, "Certainly the character of these deposits, which consist largely of fine water-laid silts, indicates that they were laid down under conditions favorable to Lower Cambrian forms of life and to the preservation of their remains. The universal absence of fossils in these rocks may, therefore, indicate that they were deposited before the advent of the Lower Cambrian fauna, that is, in pre-Cambrian time."[29]

CONCLUSIONS

1. The "Lipalian" interval and the pre-Cambrian unconformity represent two distinct concepts which should not be confused.

2. In some areas pre-Cambrian sediments pass into "Lower" Cambrian sediments with little or no break in deposition.

3. For the sake of uniformity the base of the Cambrian should, for the present, be drawn at the base of the lowermost fossiliferous formation; the practice of extending the Lower Cambrian downward through great thicknesses of unfossiliferous sediments until an unconformity is encountered should be discontinued.

Most geologists consider the coarse, poorly sorted, basal clastics to be of continental origin, while the zones bearing the lowermost fossils are undoubtedly of marine origin. Although there may well have been no actual break in deposition, the transition from continental to marine sediments should be marked by an apparent disconformity where the advancing Lower Cambrian sea re-worked the uppermost continental sediments. The sediments above and below the disconformity should be the same lithologically, but those above should reveal better sorting and the elimination of the finer material. Such a horizon, even though it transgresses time, would provide a definite boundary between sediments deposited by the Lower Cambrian sea and the earlier unfossiliferous formations.

In the Nopah Range, California section, the committee on Cambrian stratigraphy placed the base of the Cambrian at the base of the Stirling quartzite.[30] Hazzard indicated a "possible disconformity" at the base of this formation,[31] although, as noted earlier, he placed the base of the Cambrian some distance below this horizon.

4. Marine deposition may have been taking place for some time preceding the first appearance of fossils, resulting in conditions suitable for their preservation.

5. The period during which animals acquired the ability to form shells may have been relatively short, as indicated by the time required for changes of comparable magnitude in later geologic history.

6. The nature of the first fauna of the Lower Cambrian suggests that organisms did not possess the ability to form shells at the beginning of Cambrian time but quickly acquired the ability when environmental conditions or pressure of competition with other forms of life necessitated rapid change.

7. If statements listed under 4, 5, and 6 above are logical, the concept of the "Lipalian" or "lost" interval is unnecessary.

ACKNOWLEDGMENTS.—Appreciation for many helpful comments and criticisms is expressed to Dr. Louis M. Cline of the University of Wisconsin, although Dr. Cline is in no way responsible for the conclusions presented above.

[29] "Geology of Alabama: The Paleozoic Rocks," *Ala. Geol. Surv. Spec. Rept. 14* (1926), p. 60.

[30] Chart I of ftn. 5.

[31] See ftn. 7.

BASE OF THE CAMBRIAN SYSTEM[1]

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ABSTRACT

In the western part of the Great Basin region many thousand feet of marine strata lie conformably beneath the earliest Cambrian faunal (time) horizons. Along the trends of transgression these basal deposits disappear progressively until Lower Cambrian and, finally, Middle Cambrian faunas occur in the beds which lie directly upon pre-Cambrian rocks. Thus Cambrian sedimentation began much earlier in some places than in others; and, if we regard a basal unconformity as the lower limit of the Cambrian system, this limit will vary in time from the age of the strata at places where the faunal and physical bases coincide to the earlier but uncertain age of the lowermost stratum conformably underlying the recognized Cambrian. This variable duration of the "Lipalian interval," together with other similar Cambrian relationships, proves the inadequacy of physical criteria as a satisfactory basis for the establishment of time-rock boundaries.

Since faunal correlation generally is much more precise than diastrophism as a time index, the time-stratigraphic units of that portion of the geological record in which diagnostic faunas occur (Paleozoic and higher) should be delimited biologically. In the interest of local and interregional precision of definition and of validity of stratigraphic concept, the base of the biozone of the trilobite genus *Olenellus* is proposed as the base of the Cambrian system.

INTRODUCTION

Recent progress in regional studies on Cambrian stratigraphy has shown conclusively that the conventional treatment of rock units, with regard to their time relationships, is inadequate. H. G. Schenck and S. W. Muller[2] show that lithologic boundaries, including unconformities, play no consistent role in the demarcation of time-stratigraphic units. In the light of the conclusions of these authors, together with regional studies on the early Paleozoic rocks of the southern Great Basin region, it is evident that the lower limit of the Cambrian system can no longer be regarded as a problem to be solved on the basis of local physical relationships.

The upper limit of the Cambrian, like the boundaries between most of the higher units, has been established, in the last analysis, primarily on a faunal basis. Since the Cambrian is the lowermost of the systems generally amenable to more or less precise time definition and since virtually all geologists associate the beginning of Cambrian time with the initiation of correlative faunas (time indices), the need is apparent for a base to this system and a beginning of the Paleozoic era which exhibits a semblance of world-wide time equivalency.

The scope and purpose of this paper does not include a discussion of the original definition of the Cambrian system. This phase of the problem has been adequately covered by M. Grace Wilmarth[3] and by others. It will suffice to point out that the original British type section has long since been abandoned in so far as the Lower Cambrian and its base are concerned.

Nor is it the purpose here to discuss the Lower Cambrian Waucobian series in terms of the strata represented in its type section and their physical relation-

[1] Read before the annual meeting of the Geological Society of America, Chicago, December 27, 1946. Published by permission of the director, Nevada State Bureau of Mines.

[2] "Stratigraphic Terminology," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 419–26.

[3] "The Geologic Time Classification of the United States Geological Survey Compared with Other Classifications," *U.S. Geol. Surv. Bull. 769* (1925), pp. 92–103.

ships.[4] In view of the structural complexities of the Inyo region, more comprehensive field studies are needed before these rocks can be employed as a satisfactory standard.[5] However, the fact is significant, that, as generally recognized, the Lower Cambrian of Waucoba Springs and elsewhere is characterized by species of the trilobite genus *Olenellus*.

UNCONFORMITIES AS TIME INDICES A FALSE CONCEPT

The classical approach to this problem, as it too often has been with other boundary dilemmas, is the obvious outgrowth of the original catastrophist viewpoint. It is natural that scientists a century and more ago should choose the unconformities to bound their chance type sections. It is further understandable that many of the countless hiatuses throughout the world should be correlated "approximately" with those marking the "boundaries" between the original systems, thus providing a basis for the widespread belief that diastrophism should be the ultimate basis for subdivision of the geological record. It is not the writer's purpose to offer an extended discussion of the role of diastrophism in stratigraphy. Nevertheless, it seems pertinent to invite attention to the altogether too common misconception of the "diastrophism concept" that an unconformity should be generally, if not universally, present (on the continents) at the base of the Cambrian system or that unconformities may be regarded as time-rock division boundaries rather than as merely one of the many expressions, both physical and biological, of more causal phenomena.

The contemporaneity or near-contemporaneity of geographically separated diastrophic events is often falsely assumed. In the absence of fossils many stratal sequences have been assigned to one time unit or another merely because they are conformable with beds belonging to that unit. Such practice, within reason, is often justified, but it is clearly erroneous to assume that hiatuses immediately preceding or following such questionably assigned sequences are sufficiently contemporaneous to be regarded as time indices or division limits. In numerous other cases fossiliferous strata, time equivalents of which are not present in the type sections, are assigned to the underlying or overlying system on the basis of their faunal affinities to one or the other. This practice is logical, and it obviously leads to the ultimate filling of gaps represented by the unconformities at the type sections. As the gaps are so filled, there remains no choice but to select a faunal or time boundary to separate the two systems in question. Otherwise, if physical relationships are employed locally to establish the boundary, strata of a given age may be assigned to the top of one system in some areas and to the base of the superjacent system in others. In consequence, events and phenomena belonging to the early or late portions of geologic periods may be unnecessarily miscorrelated, and thus the very purpose of employing a time scale in geology loses its meaning for an appreciable portion of the record.

Another difficulty in utilizing unconformities as time indices is the fact that the basal strata immediately above a given break may vary in age from place to place. In addition to these arguments,

[4] C. D. Walcott, "Cambrian Sections in the Cordilleran Area," *Smithsonian Misc. Coll.*, Vol. LIII, No. 5 (1908), pp. 185–88.

[5] The pre-Cambrian and early Paleozoic rocks of the Inyo region are currently under study by J. H. Maxon ("Pre-Cambrian Stratigraphy of the Inyo Range" [abstr.], *Proc. Geol. Soc. Amer., 1934* [1935], p. 314).

there is the evident fact that no unconformity can constitute a time boundary. Time continued and physical events occurred during the interval represented, although the boundary may be established within the hiatus

RELATIONSHIPS IN THE SOUTHERN GREAT BASIN AREA

To consider the question of the base of the Cambrian system, in the light of the preceding discussion, attention is directed to the regional time-stratigraphic relationships in the southern Great Basin region (Fig. 1).

In the Nopah Range of southeastern California, the excellently described sections of J. C. Hazzard[6] show the zone of *Olenellus* in the upper part of the Wood Canyon formation, as defined by T. B. Nolan,[7] and the lower part of the overlying strata, which are at present without satisfactory designation. Here the genus *Olenellus* occurs through a stratal thickness of approximately 900 feet. Conformably below, an 8,521-foot sequence of unfossiliferous strata separates the *Olenellus* fauna from the pre-Cambrian erosion surface upon which these rocks were deposited. This sequence consists of the Noonday dolomite, the Johnnie formation, the Prospect Mountain quartzite, and the lower 1,900 feet of the Wood Canyon formation, all of which has been referred by Hazzard[8] and Nolan[9] to the Lower Cambrian series because of an absence of an unconformity within. All these pre-*Olenellus* strata, together with several hundred feet of *Olenellus*-bearing beds (over 9,000 feet in all), accumulated in this portion of the Cordilleran geosyncline before the sea advanced southeastward over the margin of the trough to the area now occupied by Frenchman Mountain, near Las Vegas, Nevada.

At Frenchman Mountain the post-Proterozoic sedimentation began only a short time before the regional disappearance of *Olenellus*, for here the trilobites, which appear to be confined to a stratal thickness of 32 feet, are separated from the basal unconformity by only 390 feet (310 feet of Prospect Mountain quartzite and the lower 80 feet of Pioche shale).

Continuing eastward to Western Grand Canyon,[10] *Olenellus* occurs a mere 182 feet above the unconformity; and, according to E. D. McKee,[11] its horizon is finally occupied by the advancing Prospect Mountain facies in the vicinity of Granite Park,[12] about 33 miles eastward. Thus, at an unknown point in the Grand Canyon east of Granite Park, the basal sediments of the Cambrian sea were deposited contemporaneously with the terminus of the *Olenellus* zone in this region; while in the Nopah Range of California, only about 200 miles distant, the highest

[6] "Paleozoic Section in the Nopah and Resting Springs Mountains, Inyo County, California," *Calif. Jour. Mines and Geol., State Mineralogist Rept.*, Vol. XXXIII (1938), pp. 273–339.

[7] "Notes on the Stratigraphy and Structure of the Northwest Portion of Spring Mountain, Nevada," *Amer. Jour. Sci.*, Vol. XVII (5th ser., 1929), pp. 461–72.

[8] Ftn. 6.

[9] "The Basin and Range Province in Utah, Nevada, and California," *U.S. Geol. Surv. Prof. Paper 179-D* (1943), p. 147, and Pl. 40, opp. p. 152.

[10] E. T. Schenk and H. E. Wheeler, "Cambrian Sequence in Western Grand Canyon, Arizona," *Jour. Geol.*, Vol. L (1942), pp. 882–99.

[11] "Cambrian History of the Grand Canyon Region," *Carnegie Inst. Wash. Publ. No. 563* (1945), p. 28.

[12] The questionable suggestion in Fig. 1 that *Olenellus* beds at Granite Park represent a relict facies fauna is offered here merely as an alternative to McKee's (*ibid.*, pp. 135–36) conclusion that ". . . . the sea apparently advanced in steps with pauses between. . . . ." Either explanation serves the purpose of the present study equally well.

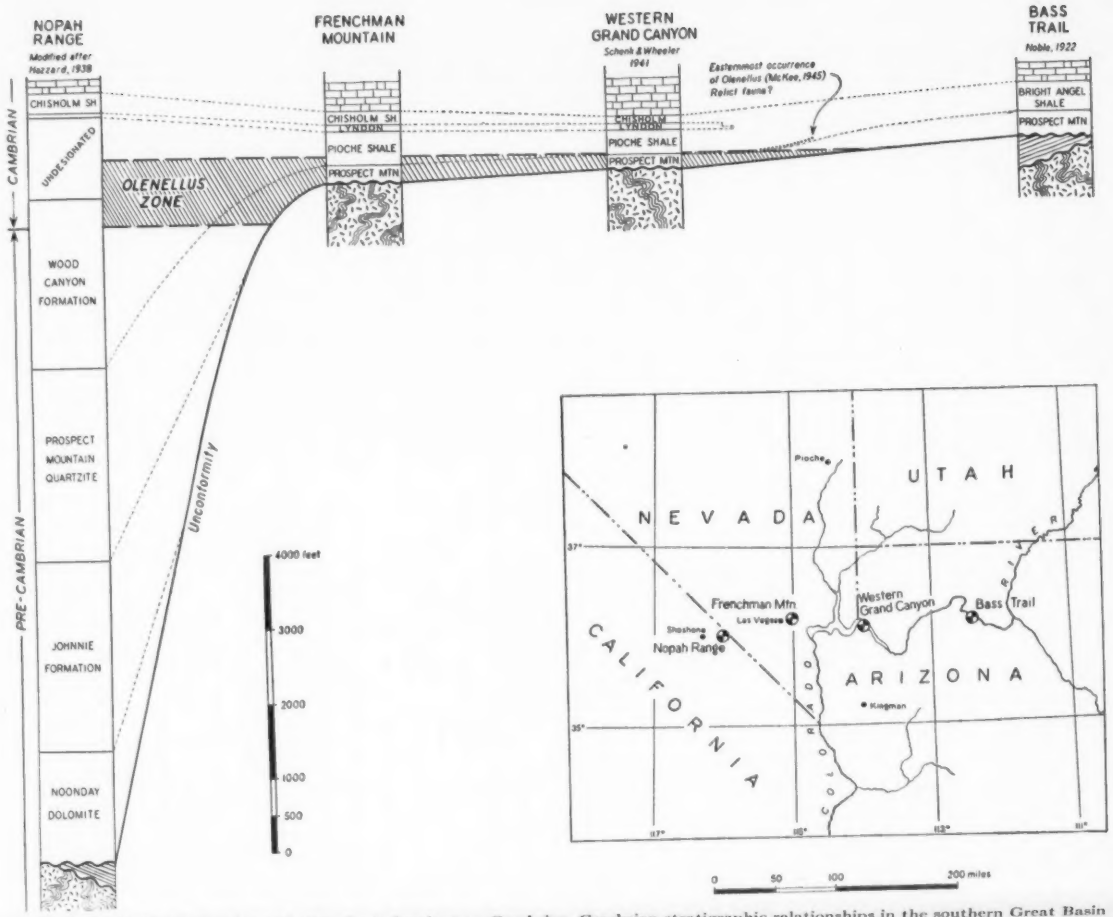

FIG. 1.—Index map and correlation chart showing pre-Cambrian–Cambrian stratigraphic relationships in the southern Great Basin

occurrences of this genus are separated from the same unconformity by approximately 9,400 feet!

Under these conditions, can the basal beds above such an unconformity be regarded as a time horizon? Obviously not. And, if not, when and where did the Cambrian sedimentation begin? While the science of geology in general is becoming increasingly quantitative and more precise, *how can we continue to indulge in a concept which regards the base of the Cambrian system as a time horizon but determines that base by physical criteria that are not amenable to interregional correlation?* If we are to continue to regard the beginning of Cambrian time as a "date of reckoning" or a date comparable to the beginning of the Christian era in human history, this system must be given a starting-point in time If we are to regard earliest Cambrian as the time of widespread appearance of faunas amenable to interregional correlation, an appropriate time-stratigraphic (faunal) designation of the base of the system is mandatory. Otherwise, we greatly increase the risk of assigning rocks of a given age to the Cambrian in one region and to the pre-Cambrian in another. To illustrate: in the northern Rocky Mountains an unconformity separates the pre-Cambrian Belt series from Middle Cambrian strata; yet there is no assurance that the uppermost Beltian beds may not be in part contemporaneous with the supra-unconformital Nopah sequence in California. Nor do we have reason to conclude that the lower part of the Sinian system (see p. 158), which conformably underlies the Cambrian of China, differs in age from the higher portion of the Belt series or other strata assigned to the late pre-Cambrian on physical evidence.

PROPOSED BASE OF THE CAMBRIAN SYSTEM

As the most widespread of the earliest faunal (time) horizons admitting of such interregional correlation, the base of the biozone of *Olenellus*[13] is proposed as the base of the Cambrian system. This designation, of course, does not perforce establish the base of the Cambrian at all localities. As in the case of other time-stratigraphic boundaries, identification is contingent upon the local presence of diagnostic faunas and success in determination of the relative ages of the strata in which these faunas make their initial appearances in different regions. For example, in the region discussed herein, the known maximum range of *Olenellus* is found in the Nopah Range, where it extends through approximately 900 feet of strata. In other regions the *Olenellus* biozone is reported to extend through somewhat greater thicknesses. To what extent the differences result from differential rates of sedimentation and to what extent they manifest facies changes or time involved in migration is not known at present. However, until otherwise indicated by additional biostratigraphic data, the lowermost known occurrence of *Olenellus* in this region is tentatively regarded as the base of the biozone of *Olenellus*. Accordingly, the base of the Cambrian system is here tentatively placed approximately 1,900 feet above the base of the Wood Canyon formation in the Nopah Range, as that base was designated by J. C. Hazzard.[14] The pre-

[13] The *Olenellus* biozone includes the *Bonnia* zone, which is also characterized by *Olenellus*.

[14] Pp. 307–12 of ftn. 6, and chart, p. 278. Hazzard admits that the Wood Canyon formation in the Nopah Range includes more beds than were placed in the formation by Nolan at the type locality. The basal 1,535 feet are predominantly arenaceous and perhaps should be included in the underlying

FIG. 1.—Index map and correlation chart showing pre-Cambrian–Cambrian stratigraphic relationships in the southern Great Basin

Olenellus-bearing strata of the Wood Canyon, together with the successively underlying Prospect Mountain, Johnnie, and Noonday formations, which aggregate more than 8,500 feet, are assigned to the pre-Cambrian.

The Cambrian Subcommittee of the National Research Council Committee on Stratigraphy[15] points out that L. F. Noble and J. F. Mason believe that the Johnnie formation and the Noonday dolomite are to be regarded as pre-Cambrian. Thus they would place the boundary at the base of the Prospect Mountain ("Sterling") quartzite. This opinion is an appreciable advance in the right direction, but it still offers a solution which is only local in nature and, moreover, not amenable to time correlation. Unless such a lithogenetic boundary is believed to coincide locally with a selected or established faunal boundary, its choice is inconsistent with the facts of time-rock relationships as they are understood at present.

Attention is invited to the fact that the lithogenetic equivalents of the Prospect Mountain quartzite and pre-Cambrian portion of the Wood Canyon formation, as present in the Nopah Range, are not everywhere assignable to the pre-Cambrian. Along the eastward trends of transgression, these shales and quartzites become progressively younger, passing successively from the pre-Cambrian, first, into the Lower Cambrian and, finally, into the Middle Cambrian series. And, conversely, in this easterly direction the pre-Cambrian–Paleozoic boundary courses downward through these lithologic units until it meets the upwardly transgressing regional unconformity.

These general relationships respecting the base of the Cambrian system are by no means confined to the southern Great Basin area. A review of time-stratigraphic relationships in the southern Appalachian region reveals similar conditions. The variable thicknesses of strata below and conformable with those containing the lowermost Cambrian faunal horizons, together with the faunal evidence from younger strata, attest to the geographic variation in the age and duration of the preceding erosion interval; and, as in the Cordilleran region, these differences become even more marked when a comparison is made between the deposits of the Appalachian geosyncline and the bordering areas. R. C. Moore[16] suggests that some of the trough sediments may belong to the late Proterozoic rather than to the Early Cambrian. The Cambrian Subcommittee[17] has removed several of the supra-unconformital formations from the Cambrian, but the base of the Cambrian in each case was placed at a convenient lithologic contact, the contemporaneity of which cannot be proved for any considerable distance.

Further, the same general relationships are found in the development of the Paleocathaysian geosyncline of eastern China.[18] In the border region between Jehol and Hopei provinces, the late pre-Cambrian Sinian system, which has a maximum thickness of more than 17,500

Prospect Mountain ("Sterling") quartzite. In that case the base of the Cambrian would be placed 343 feet above the base of the Wood Canyon formation.

[15] "Correlation of the Cambrian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), p. 996.

[16] *Historical Geology* (New York: McGraw-Hill Book Co., 1933), p. 126.

[17] Pp. 997–98, Chart 1 and nn. 25, 26, 29 of ftn. 15.

[18] J. S. Lee, *The Geology of China* (London: Thomas Murby & Co., 1939), pp. 67–80 and 211–14.

feet, is conformably overlain by Lower Cambrian strata containing the widespread *Redlichia* fauna. From this maximum the thickness of the Sinian portion of this great continuous sequence diminishes to nothing in parts of southern Shansi and northern Honan. In the southwestern part of the Luliang Range, Cambrian shale rests directly upon the Archean.

Apparently, this problem in eastern Asia was first appreciated in its true light by A. W. Grabau,[19] who separated the Sinian system from the Cambrian on a faunal basis, although he regarded it as the first system of the Paleozoic. Thus, for the first time, a time-stratigraphic base for the Cambrian was established. Through its employment a much truer concept of regional developments in the Paleocathaysian region has been developed than would have been derived if the time-transgressing sub-Sinian unconformity had been employed as the basal unit of the Cambrian in China.

Similarly, in North America the true sequential relationships can be better visualized through the establishment of a time-stratigraphic base for the Cambrian system. Furthermore, the establishment of such a base at the lowermost of the horizons amenable to general interregional correlation would denote a logical separation of the entire geological record into two parts—those strata which do lend themselves to general time-stratigraphic treatment (Cambrian and later) and those which do not (pre-Cambrian).

When the use of a time-stratigraphic base becomes common practice on this continent, the question of general world-wide contemporaneity of the base selected or of the contemporaneity of any time-rock boundary that might prove more appropriate will then be among the detailed problems to be solved in the light of constantly accumulating biostratigraphic data.

[19] "The Sinian System," *Bull. Geol. Soc. China*, Vol. I (1922), pp. 44–88.

ON THE STRUCTURE OF *PSARONIUS SINENSIS* FROM THE OMEISHAN BASALT SERIES IN SOUTHWESTERN CHINA

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The Omeishan basalt is the name given by Y. T. Chao to a thick series of volcanic lavas of the Permian age covering an enormous area in southwestern China. The type locality of the lavas is the Omei Mountain of western Szechuan. Normally this basalt series is underlain by the Lower Permian Yangsin limestone with the leading fossils *Neoschwagerina* and *Wentzelella timorica* and is overlain by the *Gigantopteris* coal series of probably Middle Permian or Saxonian age.[1]

In a paper published in 1942 in the *Bulletin of the Geological Society of China*, the writer described in detail a particularly interesting and well-preserved specimen of Psaronieae discovered in 1941 by C. J. Peng in the Omeishan basalt series in the district of Weining in western Kweichow, probably from the interbasaltic sediments of that series. The species was named *Ps. sinensis* sp. nov. and is probably of Middle Rotliegende age.[2] The present report summarizes the results of the investigation of another specimen (Fig. 1) discovered by the same collector in the same locality. This specimen appears to be a fragment of the so-called "Luftwurzelmantel" of the same species described by the writer in 1942.[3]

[1] H. C. Sze, "Über ein neues Exemplar von *Psaronius* aus dem Omeishan Basalt in Weining (Kweichow) mit besonderer Berücksichtigung des Alters des Basaltes in Südwestchina," *Bull. Geol. Soc. China*, Vol. XXII (1942), pp. 105–31.

[2] *Ibid.*, pp. 123–24.

[3] *Ibid.*, pp. 105–31.

Central portion of the stem.—To go into more detail regarding the anatomy of *Ps. sinensis*, the central vascular system proper of the stem, as has been previously demonstrated and is again shown in this paper, consists of a great number of more or less regularly disposed, elongated steles which have the typical concentric structure, each consisting of a band of wood surrounded by phloem. It follows that a survey of the orientation of the steles may furnish information of great value for the determination of the habit of the plant. Figure 2 has been prepared to demonstrate this plainly. The more minute histology of our specimens has also been worked out with a fair amount of detail. The numerous elongated steles as seen in transverse sections are strongly curved and somewhat concentrically arranged. The xylem band, which is the most conspicuous feature of the stele, is from five to about nine cells in thickness. The tracheids of the metaxylem present nothing out of the ordinary; they are all of the scalariform type so common in the Filicales. The tracheids are nearly isodiametric in transverse section and measure about 70–250 μ in diameter. The xylem parenchyma is not clearly distinguished. Like many other species of *Psaronius*, the protoxylem groups cannot be definitely delimited from the metaxylem. It is often stressed that the siliceous constitution of all the material seems to be unfavorable to the preservation of such delicate structures as the spiral or

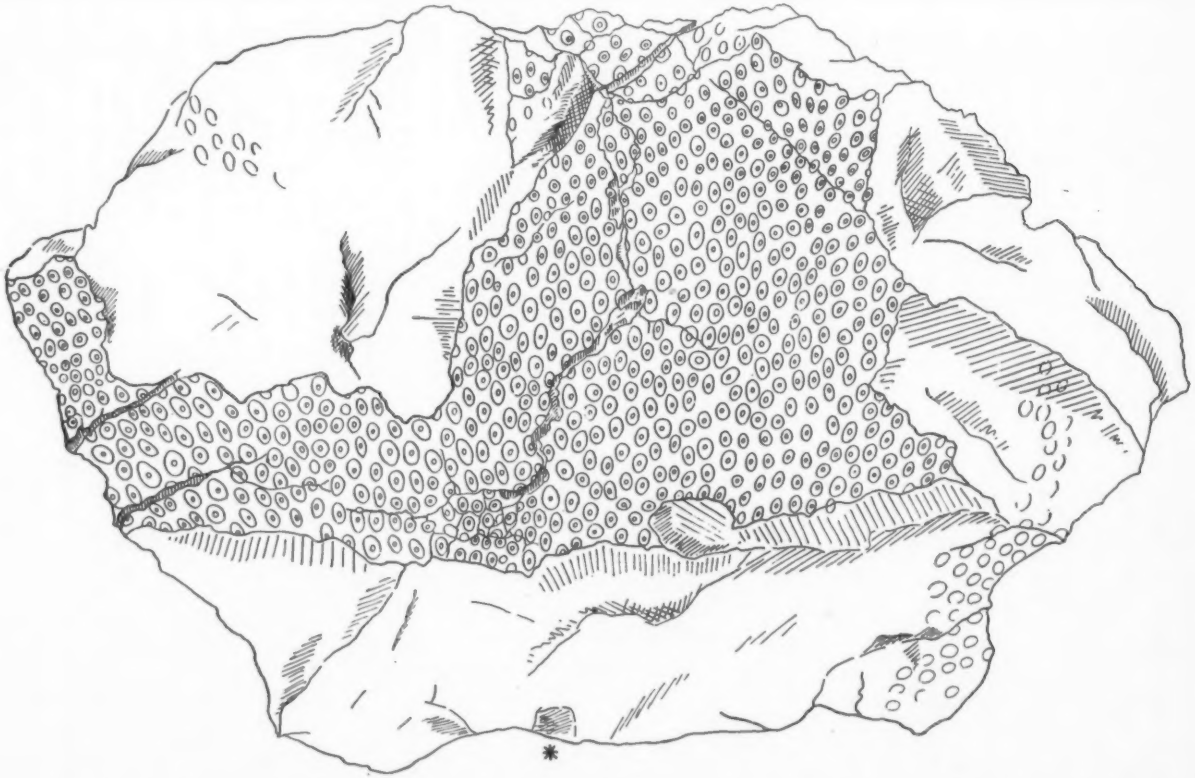


FIG. 1.—Sketch of a transversely cut face of a larger specimen of *Psaronius* in the collection, showing the orientation of the numerous adventitious aerial roots in the root mass. The two specimens of Figures 1 and 2 might belong to the same stem. Note an asterisk on left side of the sketch. This part coincides with that part of Figure 2 marked also with an asterisk. (×7/8.)

annular thickening of the walls of the protoxylem, even though they were originally present. It appears that the protoxylem of our specimen may be endarch and limited to a very small amount, forming a number of small groups on the inner edge of the xylem. On both sides of the xylem the phloem zone is scarcely recognized. It is evident that the phloem tissue was crushed and decomposed during the process of silicification. Also the parenchymatous ground tissue is for the greater part crushed and decomposed, the cavity being filled with silica. In rare instances the parenchyma cells of the ground tissue are still preserved (Pl. I, *4*). The cell walls are thin and delicate. The cells, isodiametrical in transverse as well as in longitudinal sections, measure about 40–90 μ in diameter. There are no irregular bands or patches of sclerenchyma, which are so characteristic of *Ps. infarctus* Ung., to be found in our species. Also the continuous sclerenchyma ring which surrounds the stem and which is very characteristic of *Ps. brasiliensis* Brongn. has not been found in the present stem.

Leaf traces.—Owing to the insufficient and incomplete material available, the position of the leaf traces cannot be definitely determined. On one side of the stem there are two oppositely disposed, strongly curved, horseshoe-shaped bands (Fig. 2, lt_1 lt_2) that may well be interpreted as the outgoing leaf traces. The bands are here more slender and delicate than the remaining steles. The question whether those on the right and left sides of the stem—four similar horseshoe-shaped slender bands (Fig. 2, lt_3–lt_6)—can also be regarded as leaf traces must be left open for the present.[4] Plate II, *3*, illustrates the general aspect of a part of a leaf trace (lt_1 of Fig. 2). The trace consists of a narrow xylem strand which is invested by the rather delicate phloem

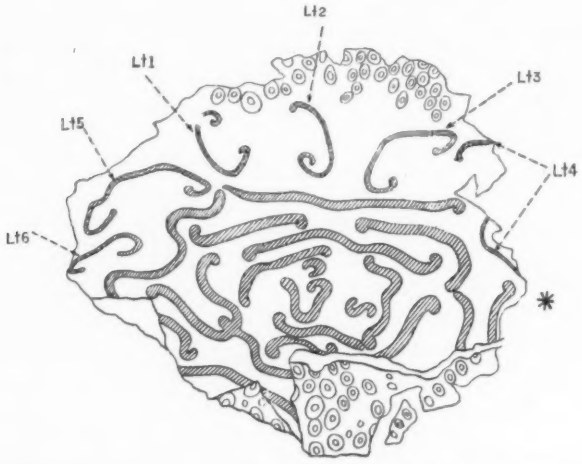


FIG. 2.—Sketch of a transverse section of *Psaronious senensis* Sze showing the orientation of the elongated steles in the central portion of the stem. Note the six smaller and slender, horseshoe-shaped bands (lt_1–lt_6) which might be interpreted as leaf traces. (Natural size.)

[4] *Ibid.*, p. 107.

tissues. The comparatively larger and round cells (Pl. II, *3*) may well be regarded as the characteristic sieve tubes.

Roots.—The mass of the specimen is, as in other species, a mat of adventitious aerial roots, which differs very little within the genus. The vascular structure of the roots is polyarch and is of extreme stellate form. The number of xylem angles is usually five, occasionally also three or four. Phloem and cortex are quite well preserved. The inner cortex is composed of short-celled parenchyma, while the outer cortex is strongly constructed of narrow, thick-walled fibers (sclerenchyma). The thickness of the cell walls of the sclerenchyma measures about 22 μ, while the diameter of the cells is 30–40 μ. As seen in the cross sections, the cells are more or less round, with or without intercellular space. The parenchymatous cells of the inner cortex are sometimes well preserved (Pl. III, *1*). The elements are usually large and thin-walled, measuring about 50–240 μ in diameter. The form of the cells is more or less isodiametrical in cross, as well as in longitudinal, sections. In many instances the parenchymatous cells in the inner cortex were strongly crushed and have perished, forming a wide empty space which has been filled with chalcedony. Between this parenchymatous inner cortex and the central stellate vascular bundles, there is a narrow zone of thick-walled fibers, which might be termed the sclerenchymatous sheath (Pl. II, *1*, *2 sks;* Pl. III, *1*, *2*, *sks*). A few layers of delicate parenchymatous tissues are still to be recognized within this sclerenchymatous sheath. An endodermis has not been clearly distinguished. The central vascular bundles are polyarch, with mostly five or six, occasionally three or four, xylem angles. At the foremost angles of the xylem are situated the smallest elements which no doubt constituted the protoxylem, and longitudinal sections show that they alone are spirally thickened; the remaining elements of the xylem (metaxylem) are scalariform. The tracheids of the metaxylem measure about 40–220 μ in diameter. The phloem is often well preserved. It consists of large, thin-walled, much-elongated elements with oblique end walls. The phloem fills the bays of the stellate xylem, but it does not extend around the ends of the arms, that is, it does not surround the protoxylem. Though sieve plates have not yet been observed, the whole character of the tissue indicates that it is of the nature of phloem.

The adventitious aerial roots that form the closely felted mat around the stem are embedded in and held together by the dense, filamentous tissues that take a radial course (i.e., the tissues run in a horizontal direction). The whole mass is closely matted together to form a practically continuous tissue. Figure 1 illustrates the general aspect of the broad zone of aerial roots. The opinion may here be hazarded, however, that the two fragmentary examples just mentioned (Figs. 1 and 2) might belong to one and the same stem or perhaps even might be split from one and the same block. Although a final decision does not yet seem possible, it would not seem to be too rash to assume the identity of the two examples shown in Figures 1 and 2.

Comparison.—Psaronius sinensis is so distinctly different from the several other species of the genus which have been described that there can be no question of its validity. The only species of *Psaronius* previously described that is well enough preserved to permit accurate comparison is *Ps. quadrangulus* Sterzel

from the Middle Rotliegende of Chemnitz in Saxony. According to Hirmer,[5] this species is characterized by

> Stamm mit viergliedrig alternierenden Wedelquirlen. In Querschliff zeigen such je vier in einen Kreis gestellte Platten immer alternierend mit de je vier des nächst äusseren und nächst inneren Kreises. Wenn es zur Abgabe des Blattspurstränge (im äussersten Bündelkreis) kommt, werden diese so gebildet dass jede Platte am Rand links und rechts ein schmales Band abtrennt und je zwei Bänder mit den einander zugekehrten Seiten zu einem hufeisenförmigen Blattspurstrang zusammentreten.

According to this description, *Ps. quadrangulus* approaches *Ps. sinensis* in size of the stems and in the orientation of the elongated steles in the central portion of the stem. Although there appear to be no essential differences between the European Middle Rotliegende species and the Chinese type, we are, however, hardly justified in assuming specific identity. Since only a single specimen of the central portion of the stem has so far been discovered, and since, furthermore, the position of the leaf traces has not yet been definitely proved in our species, the writer was inclined during his preliminary studies to identify the Chinese species as new.[6]

From the evidence of constant association, there can be little doubt that the fronds of Psaronieae were of the *Pecopteris* type and identical with those on which fructifications such as *Asterotheca* and *Scolecopteris* were borne. It is of interest to note that a small fragment of a *P. pinna* belonging probably to the groups *P.* (*Asterotheca*) *arborescens* Brongn. and *P.* (*Asterotheca*) *miltoni* Artis sp. was also obtained from our locality.[7] A reconstruction of the probable aspect of *Ps. sinensis* has been given by the writer.[8]

Geological age.—The age of the Omeishan basalt and its overlying *Gigantopteris* coal series has long been a favorite subject for discussion. From the paleobotanist's point of view, so far as the criteria are yet in hand, the basaltic series is evidently bound to the Middle Rotliegende by its petrified fossil *Psaronius*, which has very close relatives in the beds of Middle Rotliegende age of Chemnitz (Saxony), and its overlying *Gigantopteris* coal series is parallel to the Upper Rotliegende horizons in Europe. The writer has discussed this problem at great length in his previous papers.[9] At any rate, there is ample evidence indicating decisively that the flora of the *Gigantopteris* coal series in northern and southern China is Middle Permian or Saxonian in age and cannot be younger, as Dr. T. K. Huang and many Chinese geologists have suggested.[10] Additional evidence in support of this opinion is found in the occurrence of an Upper Permian index fossil *Ullmannia* aff. *bronni* Göpp. in the Talung series in that province. In his previous paper[11] the writer has tabulated the

[5] M. Hirmer, *Handbuch der Paläobotanik*, Band 1 (München, 1927), p. 1.

[6] P. 108 of ftn. 1.

[7] P. 116 and Fig. 5 of ftn. 1.

[8] P. 117 of ftn. 1.

[9] H. C. Sze, "Über das Vorkommen von *Callipteris conferta* Sternb. in der Unteren Shihhotze Serie in Central Shansi," *Bull. Geol. Soc. China*, Vol. XX (1935), p. 572; and pp. 120–25 of ftn. 1.

[10] H. R. Göppert, "Die fossile Flora der permischen Formation," *Palaeontographie*, Vol. XII (1864–65); T. K. Huang, "The Permian Formation of Southern China," *Mem. Geol. Surv. China*, Ser. A, No. 10 (1932); K. Rudolph, "Psaronien und Marattiaceae Denkschr.," *Kaiserl. Akad. Wien*, Vol. LXXVIII (1905); B. Sahni, "Permo-Carboniferous Life Provinces with Special Reference to India," *Current Science*, Vol. IV (1935), pp. 385–90; V. K. Ting and A. W. Grabau, "The Permian of China and Its Bearing on Permian Classification," *Report 16th Internat. Geol. Cong., Washington, 1933* (1934); H. C. Sze, "Über ein Vorkommen von *Ullmannia* aus dem Perm in Kiangsi," *Bull. Geol. Soc. China*, Vol. XX (1940).

[11] P. 124 of ftn. 1.

stratigraphical series of northern and southern China for the later Paleozoic and has attempted thus to show the relations between these formations and also, in a general way, the correlation of the Chinese with the European stages This tabulation is republished as Table 1.

Opinion is by no means agreed upon the possible barrier between the floral provinces of Cathaysia and Gondwana Land at the end of the Paleozoic era. In the paper published in 1942,[12] the writer has stressed the importance of

TABLE 1

CORRELATION OF CHINESE WITH THE EUROPEAN STAGES

Standard European Stages	Southwest China	North China
Thuringian = Zechstein	Talung Series	? Shihchienfeng Series
Saxonian: Upper Rotliegende / Middle Rotliegende	Lopingian (= Gigantopteris Coal Series) / Omeishan Basalt Series	Upper Shihhotze Series
Artinskian = Lower Rotliegende	Yangsinian: Maokou ls. / Chihsia ls.	Lower Shihhotze Series / Shansi Series (= Upper Yuemenkou Series)
Uralian = Stephanian	Mapingian (= Chuanshanian)	Taiyuan Series (= Lower Yuemenkou Series)
Moscovian = Westphalian	Weiningian	Penchi Series

agreeing with Professor Sahni in believing that it is rather the Himalayan geosyncline that must have been an effective barrier between the *Gigantopteris* province and Gondwana Land. Since this paper was published, the writer has received, through the kindness of Professor Sahni, a copy of his important article dealing with the theory of continental drift.[13] It is interesting to see that there is now a consensus among paleobotanists in disagreeing with the view of Ting and Grabau that the Permian basalt highland was a possible barrier between the *Gigantopteris* flora in China and the *Glossopteris* flora in India. Sahni says,[14] for instance:

> It is difficult to say how long a mere basaltic plateau[15] can have remained effective as a barrier between two closely neighbouring floral provinces, connected by land along a front extending all the way southwards as far as Sumatra. . . . . Quite probably the *Gigantopteris* flora will be found to have extended a good deal further west than Ting and Grabau believe.

With his view the writer is in full accord.

In addition to the specimens collected from Weining (western Kweichow), a small fragment of *Psaronius* from the Omeishan basalt series of the district Yiliang (eastern Yunnan) has come to the writer through the kindness of Dr. T.

[12] Sze, ftn. 1.

[13] B. Sahni, "Wegener's Theory of Continental Drift in the Light of Palaeobotanical Evidence," *Jour. Indian Bot. Soc.*, Vol. XV (1936), pp. 219–332.

[14] *Ibid.*, p. 326.

[15] In "Wegener's Theory of Continental Drift with Reference to India and Adjacent Countries," *Proceedings of 24th Indian Sci. Cong.* (1937), Sahni points out: "The plateau, however, is not known to have extended further south than the southern border of China. Apart from the improbability of such a plateau remaining effective as a barrier for any appreciable period of geological time even where it did exist, this hypothesis leaves unexplained the anomaly of two climatically distinct floras lying athwart the same latitudes along a front of something like 2,000 miles."

K. Huang of the Geological Survey of China. This fragmentary example is, unfortunately, a mass of polyarch roots without any recognizable stems. In consequence, it is impossible to assign the material to any species, as the roots do not afford specific criteria. The fragment might, however, belong to the species *Ps. sinensis*. The record is of value in that it further outlines the geographic and stratigraphic distribution, not only of the genus *Psaronius*, but also of the entire *Gigantopteris* flora in western China.

The stratigraphical and lithological relationships within the Omeishan basalt series have not yet been fully investigated, but it is certain that there must have been many interbasaltic sediments intercalated in this series. It thus appears clear that the silicified specimens here described were derived from these beds. The same view was expressed by Sahni in a letter to Professor J. S. Lee dated May 29, 1945. In this connection, the writer takes pleasure in citing the words of Sahni, expressed in his general presidential address in 1940, regarding the petrified fossils from the Tertiary Deccan intertrappean beds of India:

> If a lake or river happens to be near by, the ash settled down on the water, forming a sort of volcanic sediment in which the creatures living there find a speedy grave. But it is an immortal grave. For, through a process that is still largely a mystery to us, the bodies of these plants and animals become imperishably preserved. Particle for particle, cell for cell, the plant tissues are replaced by silica derived from the ash, or from a lava flow that may have overwhelmed the lake; and in the end we are left with an exact replica of the original in hard, indestructible silica.[16]

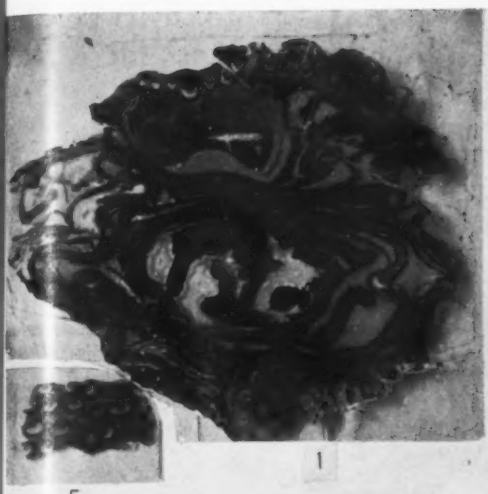
The same holds good for the present material.

Granting that the greater part of these basaltic lava flows were probably poured under the sea (e.g., in Yunnan, Sikang, and probably also in part of Szechuan),[17] the fact is clear that they should be regarded, at least in eastern Yunnan and western Kweichow, as terrestrial. It thus appears highly probable that, as Sahni has also clearly pointed out in his letter, the basaltic area in these regions would belong to the *Gigantopteris* province itself, instead of forming the barrier between Cathaysia and Gondwana Land. The results of further search in the interbasaltic sediments of the Omeishan volcanic area for many more petrifactions of the *Gigantopteris* flora are therefore eagerly awaited.

[16] B. Sahni, "The Deccan Traps: An Episode of Tertiary Era," *Proceedings of 27th Indian Sci. Cong.* (1940).

[17] Pp. 124–25 of ftn. 1.

PLATE I



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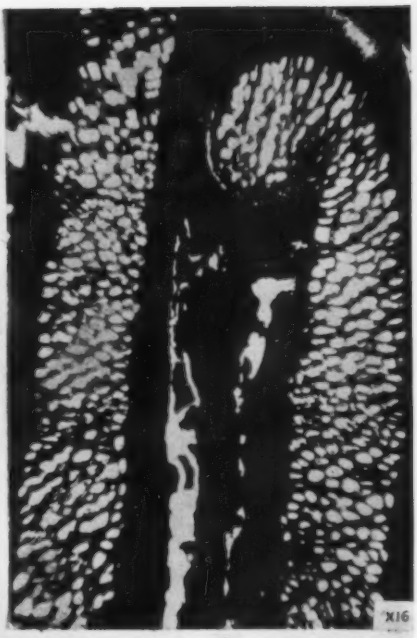

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PLATE II

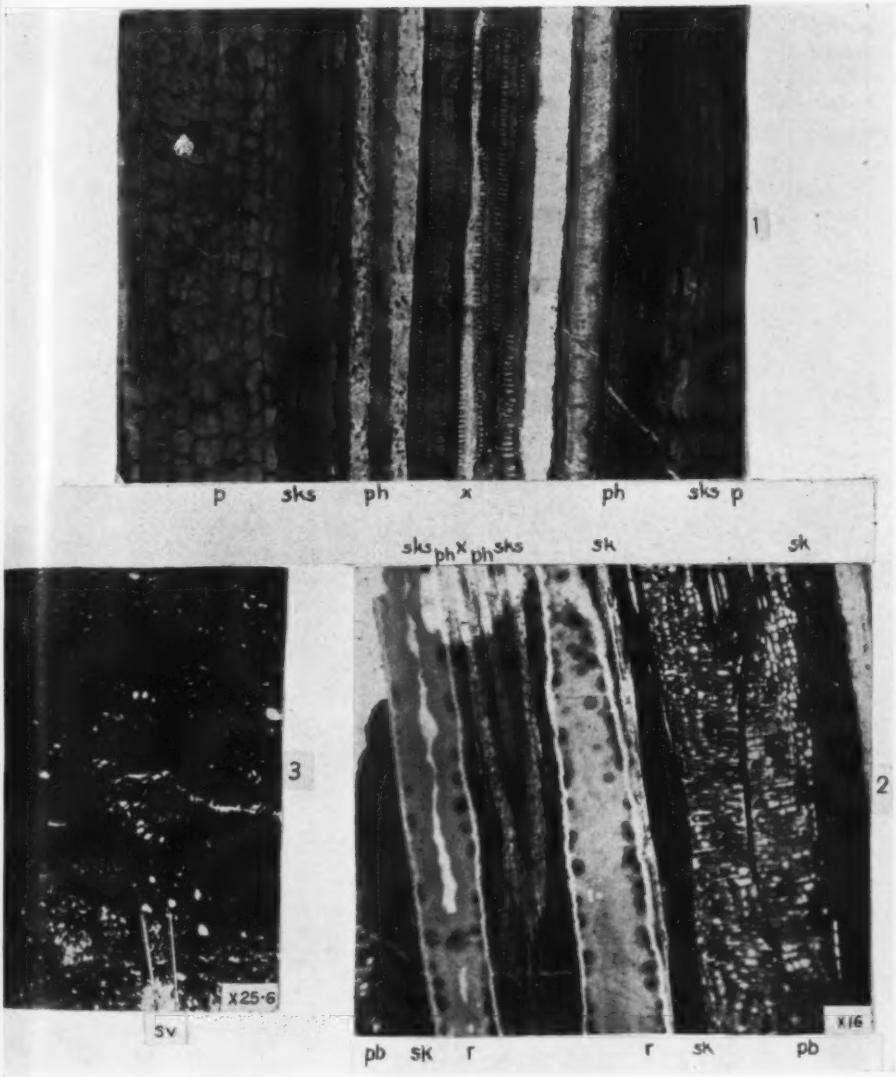
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PLATE III

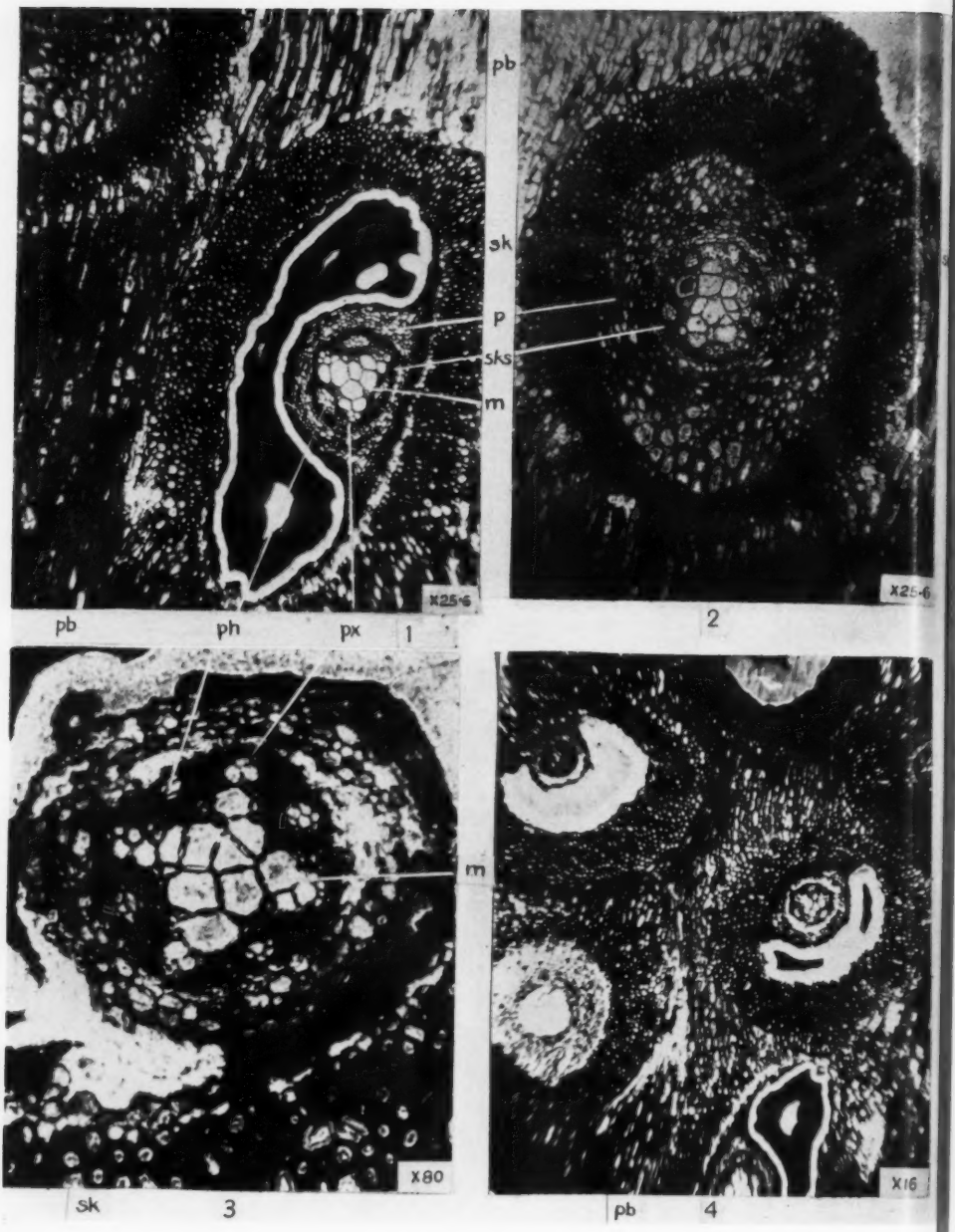

PLATE I

Psaronius sinensis SZE

1, Transverse section of *Psaronius sinensis*, showing the general aspect of the stem and the more or less regularly disposed elongated steles in its central portion. (Natural size.) *2*, Transverse section of a portion of two elongated steles, showing the tracheids of the metaxylem. The position of the protoxylem groups is not well distinguished. The phloem tissues and the parenchymatous ground tissues are fully crushed and decomposed, the cavity being filled with the silica. Xylem-parenchyma is not observed. (×16.) *3*, Longitudinal section of a portion of the stele, showing the scalariform tracheids. Note the occurrence of the irregularly disposed, more or less round, small patches in the tracheids. These small patches (*k*) are brownish in color and may well be interpreted as limonite substances. (×80.) *4*, Longitudinal section of a portion of a stele, showing the scalariform tracheids and the adjacent parenchymatous ground tissues (*p*). Likewise note the small, round, irregularly disposed brown patches in the tracheids (*k*). (×80.) *5*, Transverse section of a portion of the broad zone of the adventitious aerial roots. (Natural size.) The original specimens and slides are in the collection of the Geological Survey of China.

PLATE II

Psaronius sinensis SZE

1, Longitudinal section of an adventitious aerial root. (×80.) *2*, Transverse section of a leaf trace cut through a portion of the central stem. (×25.6.) *x* = xylem (metaxylem); *ph* = phloem; *p* = parenchyma (inner cortex); *sk* = sclerenchyma (outer cortex); *sks* = sclerenchymatous sheath; *pb* = parenchymatous "Bindegewebe"; *r* = the space originally occupied by the parenchymatous tissues of inner cortex, which were for the greater part crushed and decomposed, the cavity being filled with silica; *sv* = presumably sieve tubes of phloem. *3*, Another longitudinal section of a root at a lower magnification. Note the horizontally running parenchymatous "Bindegewebe" (*pb*). (×16.) The original specimens and slides are in the collection of the Geological Survey of China.

PLATE III

Psaronius sinensis SZE

1, Transverse section of an adventitious aerial root, showing the central stellate xylem with three xylem-angles. (×25.6.) *2*, Transverse section of an adventitious aerial root, showing the central stellate xylem with five xylem-angles. (×25.6.) *3*, Transverse section of an adventitious aerial root, showing the central stellate xylem with four xylem-angles. (×80.) *4*, Portion of the section shown in Pl. I, *5*, taken at a higher magnification to show details of the adventitious roots. (×16.) Note the six adventitious roots and the horizontally running parenchymatous tissues ("Parenchymatisches Bindegewebe" [*pb*]). *m* = metaxylem of the xylem; *px* = protoxylem; *p* = parenchyma (inner cortex); *sk* = sclerenchyma (outer cortex); *ph* = phloem; *pb* = parenchymatous "Bindegewebe"; *sks* = sclerenchymatous sheath (a tissue of narrow, thick-walled fibers which surrounds the central stellate vascular bundles and is beneath the parenchymatous inner cortex). The original specimens and slides are in the collection of the Geological Survey of China.

LARGE-SCALE SUPERFICIAL STRUCTURES—A DISCUSSION

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The structural geologist is primarily concerned with the tectonics of the earth. Because of this interest he must be prepared to identify and evaluate superficial structures that simulate those of tectonic origin. Superficial structures have long been recognized not only as annoying obstacles to structural field work but also as valuable criteria of significant processes. The best-known of these disturbances are produced (1) by sliding of beds during deposition; (2) by compaction under load; (3) by expansion due to stripping of overburden; (4) by conversion of anhydrite to gypsum; (5) by gravitational movement under erosion and intensive frost action; and (6) by ice shove.

Nontectonic structures initiated by gravitational movement down the slopes of valleys in beds of gentle dips are described in two recent papers published in England.[1] A comprehensive study of the Northampton Ironstone Field under the direction of the British Geological Survey has yielded, as a by-product, observations on, and analysis of, extensive deformations of relatively large magnitude. Only a sound knowledge of the local geology, intensive field work, and the production of detailed maps and cross sections have enabled the authors to analyze these features and to separate them from those recognized elsewhere in the region as the products of diastrophism. The result is a tightly knit, severely analytical, and convincing study whose importance and general interest to the American geologist prompts this discussion. Dr. S. E. Hollingworth and his colleagues have most kindly granted permission to redraw certain of their illustrations for publication here.

The Northampton Ironstone Field lies north of London in central England. Chalky Boulder-clay, presumably Würm I in age and correlative with the deposits of the Warthe glaciation on the Continent, blankets much of the area. New Drift, considered to be Würm II in age and hence equivalent with the Brandenburg substage of the North German Plains, lies just to the north and west of the area.[2] Beneath the drift, Jurassic rocks are disposed in open folds of gentle dip cut by normal faults, that, like the folds, strike north of west. The Upper Lias clay, 180–210 feet in thickness, is overlain by 150–300 feet of strong sandstone and limestone beds with intercalated weak strata of clay and sand. The economic importance of the Northampton Ironstone, the lower member of this upper group of beds, has warranted the detailed study leading to the recognition of three distinctive types of structure unassociated with the regional structure. These structures, as defined by the authors, are (1) the camber; (2) the gull,

[1] S. E. Hollingworth, J. H. Taylor, and G. A. Kellaway, "Large-Scale Superficial Structures in the Northampton Ironstone Field," *Quart. Jour. Geol. Soc. London*, Vol. C (1944), pp. 1–44; S. E. Hollingworth and J. H. Taylor, "An Outline of the Geology of the Kettering District," *Proc. Geol. Assoc.*, Vol. LVII, Part III (1946), pp. 204–33.

[2] Correlations from H. L. Movius, *The Irish Stone Age* (London: Cambridge University Press, 1942), Fig. 8.

with associated dip-and-fault structure; and (3) the valley bulge.

The term "camber" is introduced by the authors and is applied to an arching of beds over hills, with induced dip toward adjacent valleys. "Cambers result from a lowering of outcropping or near-surface strata. The beds are thus inclined towards the valleys, swathing the hill-tops and cloaking or draping the valley sides."[3] This new term is based on the architectural term "camber," defined as "the condition of being slightly arched or convex above."[4] It derives through the Old French *cambre*, "bent, curved," from the Latin *camerare*, "to arch over," and *camera*, "vault" or "arch."

As is well illustrated in Figure 1, a contour map constructed on the contact of the Northampton sand and the Lias clay, the beds involved in the process of cambering include all those above the Lias clay; and, as later brought out, movement also occurred in the clay. The cambers drape the interfluves, and the dip of the beds above the Lias clay conforms to the valley pattern, with an inclination resulting from downhill displacement in excess of 100 feet to the mile. The base of the Northampton beds is seen to fall toward each major valley and even toward the minor tributaries on

[3] Hollingworth *et al.*, p. 3 of ftn. 1.

[4] *Ibid.*, p. 3, n. 1.

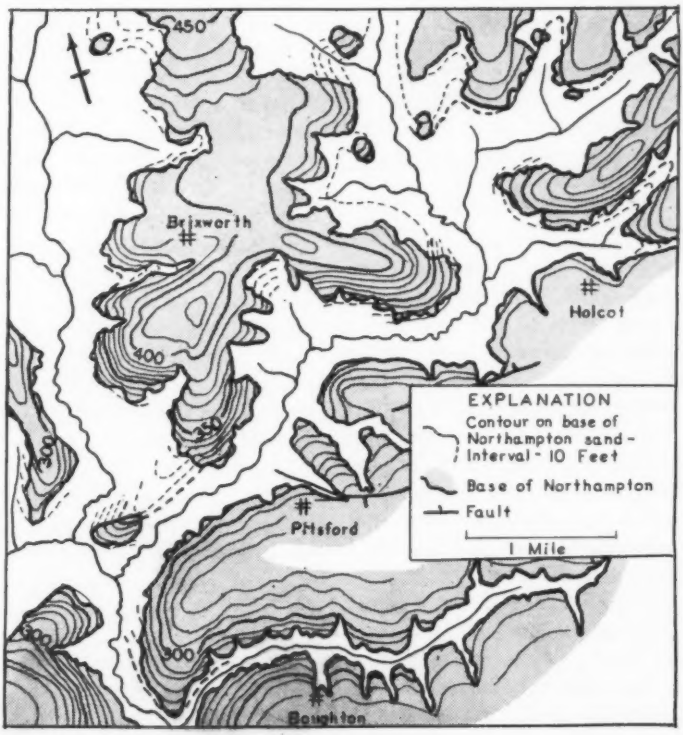

FIG. 1.—Contour map on the base of the Northampton sand to show the relation of cambers to the modern topography. (Adapted from Hollingworth *et al.*, ftn. 1.)

a surface that is obviously but a modified expression of the modern landscape. The authors present detailed sections perpendicular to the surface slopes, which further emphasize this coincidence of "structure" with the present land forms.

Glacial studies prove that, since the deposition of the Chalky Boulder-clay, erosion has removed most of the glacial drift from valleys previously cut into bedrock. Also, records of borings in certain till-choked valleys reveal the presence of cambers deep beneath the surface. The authors thus consider that

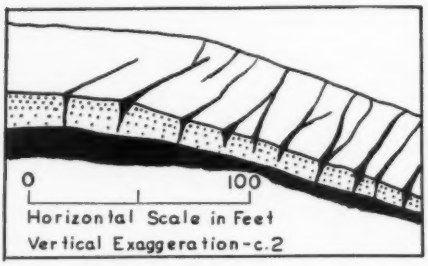

FIG. 2.—Diagram illustrating the relation of gulls to a cambered slope.

most of the cambers antedate the Fourth glacial stage, which was the last ice to cover the area.

The earlier of the two papers under discussion lists three processes involved in the development of cambers: (1) slipping of the competent beds over wet, lubricated clays of the Lias formation; (2) washing out of the clay material below the surface at the spring line; and (3) the outward flow of the Lias clay from beneath the burden of the overlying, more competent beds. The authors are not dogmatic about the dominance of any one of these causes. They leave the impression, however, that additional field study will prove that plastic flow of the Lias clay has been the most decisive of the three processes. In the second paper Hollingworth and Taylor take a stronger stand and consider that cambers result almost completely from the outward and valleyward flow of the Lias clay.

The term "gull" is suggested by the writers for those clefts in the rock which trend normal to the slope of the cambered surface. "Gull" is a local English term for a "gully" or "chasm." Derived from the Old French *gole* or *goule*, it is also used by British quarrymen for widened breaks in rocks with or without infilling.

The gulls are widened fissures or joints in the ironstone and overlying strata, steeply inclined into the hillside, wholly or partly filled with material from above, and normally associated with a camber structure. They tend to parallel each other and the surface contours, although in areas of changes in the direction of slope more complex systems occur. Figure 2, a highly schematic diagram, illustrates the attitude of gulls and their relation to surface slope and cambering.

Gulls are considered to be tensional fractures in the competent beds extended by the downward movement of cambering. The widened gulls result from continued downslope slipping. In calcareous beds the gulls, once initiated by cambering, may be widened by solution induced by water percolating along this new channel.

The authors point out the resemblance of the gulls to ice wedges,[5] but they do not believe that gulling is "explicable in terms of current contraction-crack theories of ice-wedge formation."[6] They suggest, nonetheless, that "further consideration should be given to the part that ground-ice may have played in the devel-

[5] Hollingworth *et al.*, pp. 17 and 18 of ftn. 1.

[6] *Ibid.*, p. 18, n. 1.

opment of the internal structures of a camber."[7] Ice wedging occurs in fine-grained, unconsolidated, but pergelated,[8] sediments of flat-lying areas and produces large-scale polygonal structures.[9] As such, the process is not applicable to the parallel clefts in the consolidated beds of Northampton. Nevertheless, the growth of ice masses as a cause of open clefts in rocks cannot be disregarded. Features similar even in detail to the gulls of Northampton are reported from the vicinity of Prague.[10] Here competent sandstones along valley slopes are fissured parallel to the valley strike. Many of the fractures have been broadened by ice growth within them during the Pleistocene and then infilled from above as the ice melted. Paul Kessler[11] has described open crevices in the Triassic Voltzien sandstone near Saarbrücken. He ascribes these fissures and the implied movement of large sandstone blocks toward the adjacent valleys to the growth of ice masses in incipient openings during a periglacial climate. André Cailleux[12] has reported that the chalk in the region of the lower Seine has been fissured by ground ice in similar periglacial climate. There seems no reason to discard ground ice as a factor in gulling during the periglacial climates that obtained in the Northampton area at various times during the Pleistocene. Tensional fractures, once developed, could have been effectively widened by continued ice accumulation resulting from the freezing of water fed into the gulls by capillary movement from the clays. Adjustment to this pressure would tend to express itself laterally by downslope movement of the intergull blocks. Thus, in addition to being a force in gull formation, ground ice could also have operated in promoting the process of cambering. The infilling of some of the gulls with Chalky Boulder-clay indicates movement of the cambered surfaces in post–Würm I time, even though the cambers may have been initiated at an earlier period. When the southern border of the Würm II ice stood just north and west of the Northampton area on the so-called "York line," the consequent rigorous periglacial climate would have been most effective in producing ground ice. The later cold phases of the last glacial stage would have been less effective.

A common feature in a cambered and gulled structure is a vertical displacement of the beds across the gulls. The amount of movement varies from a few inches to a few feet. The downthrow is almost without exception on the uphill side of the gull, the fault plane dipping into the hill at a high angle. This arrangement is commonly repeated across each of a series of parallel fractures, so that the blocks between consecutive gulls have downhill dips greater than the

[7] *Ibid.*

[8] From the Latin prefix *per*, "throughout," plus the Latin verb *gelare*, "to freeze" (see Kirk Bryan, "Cryopedology—the Study of Frozen Ground and Intensive Frost-Action with Suggestions on Nomenclature," *Amer. Jour. Sci.*, Vol. CCXLIV [1946], pp. 622–42, esp. pp. 635 and 640).

[9] For general reviews of ice wedging see E. de K. Leffingwell, "The Canning River Region, Northern Alaska," *U.S. Geol. Surv. Prof. Paper 109* (1919), esp. pp. 205–42; Stephen Taber, "Perennially Frozen Ground in Alaska: Its Origin and History," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 1433–1548, esp. pp. 1510–29; and F. E. Zeuner, *The Pleistocene Period: Its Climate, Chronology, and Faunal Successions* ("Ray Soc.," No. 130 [London: Quaritch, 1945]), pp. 10–13.

[10] Quido Záruba-Pfeffermann, "Periglaziale Erscheinungen in der Umgebung von Prag," *Mitt. d. tschech. Akad. d. Wissensch.*, Vol. LIII (1943), pp. 1–33.

[11] "Über diluviale Frostspalten bei Saarbrücken," *Zeitschr. d. deutsch. geol. Gesellsch.*, Vol. LXXIX (1927), pp. 75–80.

[12] "Fissuration de la craie par le gel," *Bull. Soc. géol. France*, Vol. XIII (5th ser., 1943), pp. 511–20.

general dip of the camber. Such an arrangement of the strata is called by the authors a "dip-and-fault" structure and is diagrammed in Figure 3.

In explaining the dip-and-fault structure the authors concur with C. B. Wedd that it is "the result of movement in a relatively thin, hard and brittle bed intercalated between softer and more plastic strata,"[13] and they add that surface creep may have aided in the forward tilting of the blocks. Further, they state that the "washing out, solution, or

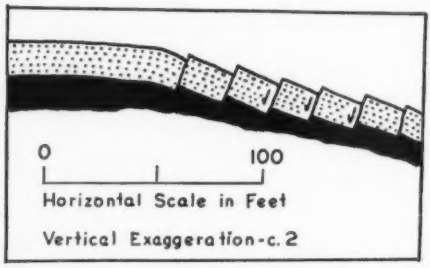

FIG. 3.—Diagram illustrating movement in dip-and-fault structures

flowage of material from beneath a massive jointed bed might be expected to lead to downhill tilting, and this would be accentuated by the consequent displacement of the centre of gravity of the individual block towards its downhill edge."[14] Finally they cite analogous structures resulting from collapse of a competent bed by undermining, the upthrow side being toward the maximum subsidence. Faulting of a similar pattern but on a large scale and of tectonic nature has been described along monoclinal folds by C. B. Hunt,[15] D. L. Babenroth and A. N. Strahler,[16] and H. E. Wright.[17]

The surface movements in competent beds usually produce the Toreva-block landslide type,[18] diagrammatically illustrated in Figure 4. In such a pattern the competent bed assumes a backward dip, and the fault plane dips downslope. The authors state[19] that true landslides, of the Toreva-block type, with accompanying reversals of dip, occur "on actively receding scarps," where cambers are limited in extent. The slopes described by Reiche as affected by Toreva-block movement are relatively steep. Small-scale, frost-induced Toreva-block sliding on high slopes of fissured sandstone near Prague is reported by Zaruba-Pfeffermann.[20] It would appear, then, that the gentle hill slopes prevalent in the Northampton area tend to inhibit normal landsliding and are an inherent part of the environment suitable for the production of dip-and-fault structures.

"Valley bulge" is a term introduced by the authors to describe a feature which in its simplest form is an anticlinal uprising coincident with the lower part of a valley. The structure may, however, occur as a complex fold, a fault block, or a

[13] In G. W. Lamplugh, C. B. Wedd, and J. Pringle, "Bedded Ores of the Lias, Oolites, and Later Formations in England," *Mem. Geol. Surv. Great Britain, Res. xii, Iron Ores* (1920), p. 145 n. (quotation and reference from Hollingworth *et al.*, ftn. 1).

[14] Hollingworth *et al.*, p. 18 of ftn. 1.

[15] "The Mount Taylor Coal Field," *U.S. Geol. Surv. Bull. 860B* (1936), esp. Pl. 19; and "Igneous Geology and Structure of the Mount Taylor Volcanic Field, New Mexico," *U.S. Geol. Surv. Prof. Paper 189B* (1938), esp. Pl. 18.

[16] "Geomorphology and Structure of the East Kaibab Monocline, Arizona and Utah," *Bull. Geol. Soc. Amer.*, Vol. LVI (1945), pp. 107–50, esp. pp. 114, 115, Fig. 2.

[17] "Tertiary and Quaternary Geology of the Lower Rio Puerco Area, New Mexico," *Bull. Geol. Soc. Amer.*, Vol. LVII (1946), pp. 383–456, esp. p. 418, Fig. 10.

[18] Parry Reiche, "Toreva-Block—a Distinctive Landslide Type," *Jour. Geol.*, Vol. XLV (1937), pp. 538–48.

[19] Hollingworth *et al.*, p. 7 of ftn. 1.

[20] See ftn. 10.

narrow horstlike mass bounded by faults. Allied valley-bottom structures exist, in which lateral movement from the sides rather than actual vertical movement appears to dominate.

Figure 5 illustrates in detail the faulting along the axis of a meandering stream valley and the associated up-bulging of the Lias clay. Lateral flow of the Lias valleyward beneath the competent beds is involved in the formation of a bulge and implies a lowering of the strata overlying the zone of greatest outflow. The result in some places is a noticeable downfold or sag along the flank of a bulge. Suggestions of such sags are seen in the sections in Figure 5. The authors' map of known valley bulges, redrawn in Figure 6, shows that bulges are unrelated to regional structure but are coincident with the modern drainage system. The authors present additional detailed maps, both surface and subsurface, which, with accompanying cross sections, drive home this relation between the bulges and the topography and constitute perhaps the most striking phenomena recorded in the two papers.

The incompetent Lias clay has moved upward in the valleys, responding to the load of the strata on the adjacent interfluvial ridges. Similar plastic flow of a weak formation under induced load is not unknown in artificial cuts,[21] and plastic rise of salt to form domes is pointed out by the authors. Although differential specific gravity plays no part in the movement of clay in a bulge as it does in the movement of salt in a dome, the two types of structure are, nonetheless, analogous.

The varied superficial structures of the Northampton area have a common genetic factor in that their development is primarily determined by the behavior, under the influence of erosion, of relatively competent strata that overlie a thick bed of easily deformed clay. The structures appear to have been initiated at different stages in the erosion and development of the present topography. The usual order of development of these features is: bulging in the early stages of the erosion of the valleys, followed by cambering and gulling as erosion cuts down through the Lias clay and isolates the overlying ironstone and accompanying beds on the ridges between valleys.

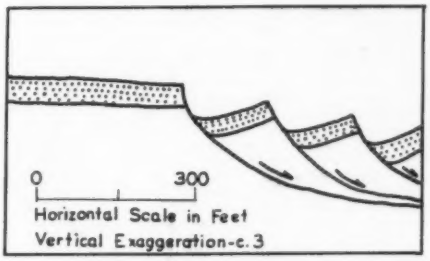

FIG. 4.—Diagram illustrating movement in Toreva-block landsliding.

The authors have ably demonstrated that these structures, in spite of their large scale, are superficial and bear no relation to coexistent forms resulting from regional diastrophism. The forms described—the camber, the gull with associated dip-and-fault structure, and the valley bulge—although in part recognized by the authors' predecessors, particularly the late Beeby Thompson, are for all practical purposes described for the first time.

As far as the writer is aware, similar features have not been described in this country. An unverified exception is the occurrence of apparently minor surface faults in the Yazoo clay of Rankin Coun-

[21] See particularly "Report of the Committee of the National Academy of Sciences on Panama Canal Slides," *Mem. Nat. Acad. Sci.*, Vol. XVIII (1924).

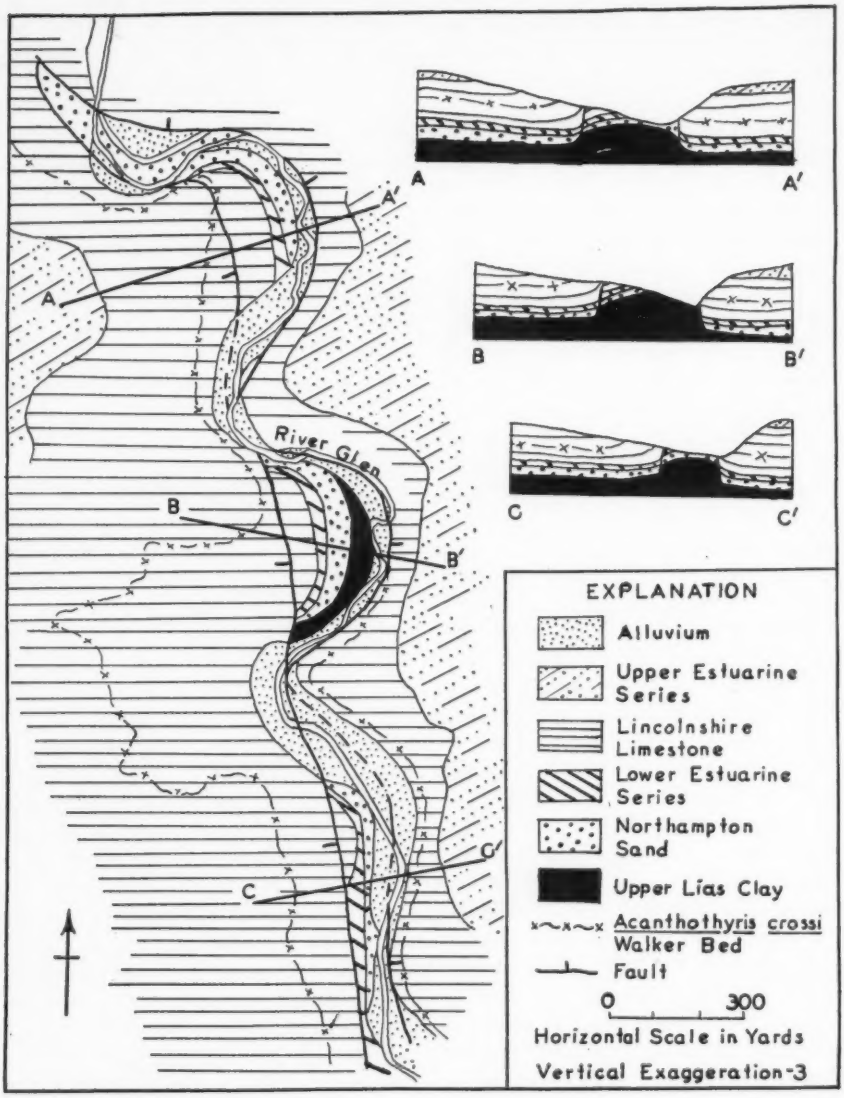

FIG. 5.—Map and sections of Glen Valley between Corby and Creeton to illustrate a valley bulge. (From Hollingworth *et al.*, ftn. 1, after F. B. A. Welch.)

ty, Mississippi.[22] Here a slight upthrow on the downhill side of the fracture, along with the relation of the fissures to local topography and stratigraphy, suggest that they may be comparable to the dip-and-fault structures of Northampton. On the other hand, they may be related to the regional fracture system of the area.[23]

semiaridity of much of the West may be against the presence there of such superficial structures. Yet some resistant strata are found in the southern Coastal Plains; and in the West, where sandstones and plastic shales are common, the climate was not always dry, having been presumably much moister during the Pleistocene stages of glacial advance

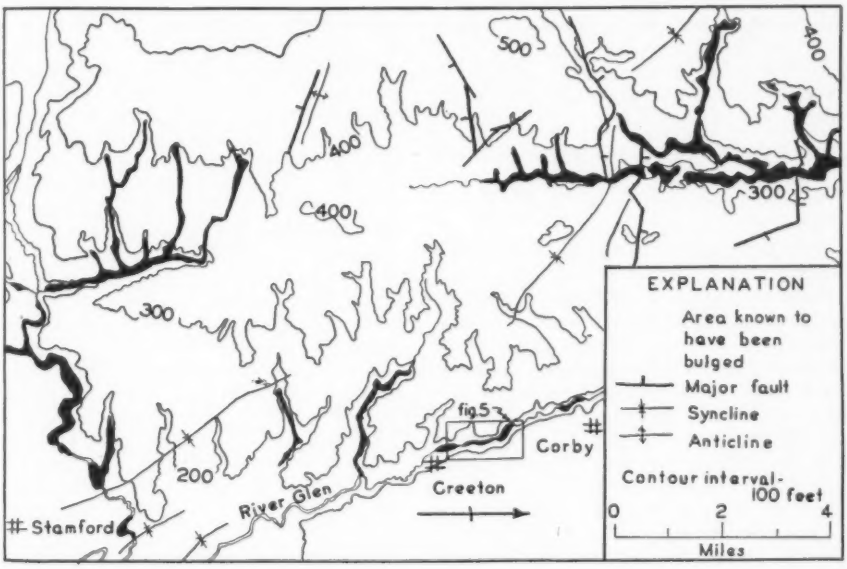

FIG. 6.—Map to show the relation of valley bulges to topography and to regional structure. The area of Fig. 5 is shown by the rectangle in the Glen Valley. (Adapted from Hollingworth *et al.*, ftn. 1.)

It is possible that structures similar to these discussed may be developed to some degree in such regions as the Coastal Plains or in the great areas of Upper Cretaceous beds in western United States. The general lack of competent formations in the Coastal Plains and the than it is today. In any event, this rarity of reference in the geologic literature to the described forms is not necessarily an index to the actual abundance of these features in the field or their importance to the geologist. Where the requisite stratigraphic sequence and topography obtain, the possibility of their existence should be suspected.

[22] Watson H. Monroe, "Earth Cracks in Mississippi," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XVI (1932), pp. 214 and 215.

[23] H. N. Fisk, "Geological Investigation of the Alluvial Valley of the Lower Mississippi River," *Mississippi River Commission, Vicksburg, Miss.* (1944).

ACKNOWLEDGMENTS.—Professor Kirk Bryan, Harvard University, brought the papers discussed to the writer's attention and encouraged this review of the problem.

REVIEWS

Contributions to Geology, 1944. (University of Texas Publication, No. 4401.) Austin, Tex.: December, 1944. Pp. 567; pls. 55. Paper, $4.25; cloth, $5.00.

This volume is a collection of ten papers (also available separately), eight of which are devoted to various phases of the paleontology of Texas. The other two are concerned with stratigraphy and present geologic background for some of the paleontologic studies.

1. "The Wilberns Upper Cambrian Graptolites from Mason, Texas." By CHARLES E. DECKER. Pp. 13–61; pls. 10; figs. 4. $0.30 separately.

This paper records the occurrence of twenty-four species and varieties of graptolites (eighteen new species, two forms unidentified specifically) referred to five genera, one of which is new; six species of hydroids (four new, one form unidentified specifically) referred to four genera; two genera and species of trilobites an unidentified worm, brachiopod and merostome. These fossils were obtained from a zone considerably older than that occupied by the widespread *Dictyonema flabelliforme* fauna of the Upper Cambrian (Canadian, referred to Lower Ordovician by some) and are stated to include more Cambrian graptolite species and varieties than have been described from all other localities in the world combined. The author includes brief discussions of graptolite morphology, relationships, Cambrian faunas, and correlations and indicates a considerable number of more important references to Cambrian graptolite literature.

2. "Stratigraphy of the Lower Pennsylvanian Coral-bearing Strata of Texas." By F. B. PLUMMER. Pp. 63–76; pls. 3; figs. 1; tables 3. $0.95 with following paper.

The lithology, distribution, thickness, subdivisions, and faunal characteristics of the Marble Falls and Smithwick formations are described. The occurrence of corals at Lower Pennsylvanian collecting localities in north central Texas and in corresponding formations of Oklahoma and Arkansas is shown in tables, and four coral zones are distinguished in this part of the Texas section.

3. "Description of Lower Pennsylvanian Corals from Texas and Adjacent States." By RAYMOND C. MOORE and RUSSELL M. JEFFORDS. Pp. 77–208; pls. 2; figs. 507. $0.95 with preceding paper.

The degree to which Pennsylvanian corals have been neglected is demonstrated by this paper which describes and illustrates sixty-two species (fifty new and five not specifically identified) referred to twenty-two genera (six new and seven not previously recognized in North America), eleven families (three new), and three suborders. A few years ago this entire assemblage would have been classified in about a dozen species and genera on the basis of external characters. Modern studies are based on internal features, however, and require careful cutting of many specimens, but this procedure is neither so exacting nor time-consuming a procedure as is generally supposed.

Corals are abundant at many places in Pennsylvanian rocks, and when they are more accurately and widely known, excellent guide fossils will probably be found among them. This paper is an outstanding contribution initiating a modern study of these fossils, and it will both stimulate, and form a basis for, much-needed additional investigations.

Brief sections on classification and terminology and a very complete bibliography are included.

4. "Smaller Foraminifera in the Marble Falls, Smithwick, and Lower Strawn Strata around the Llano Uplift in Texas." By HELEN JEANNE PLUMMER. Pp. 209–71; pls. 3; figs. 20; tables 1. $0.55 separately.

Assemblages of smaller Pennsylvanian foraminifers are closely related to the types of sediments in which they occur. Specimens from the Marble Falls limestone are mainly calcareous, whereas those from the Smithwick and Strawn shales are mostly arenaceous. This paper describes thirty-eight species and one subspecies (fourteen new and four not identified specifically) referred to twenty-three genera (one new) in eight families. Most of them are too long-ranging stratigraphically to be good guide fossils, but one useful arenaceous species appears to be re-

stricted to the Marble Falls, and several others are not known below the Strawn. Ranges of all species are shown in a table. An excellent section describes the collecting and preparing of material based on Mrs. Plummer's extensive experience in this type of work.

5. "Osteology and Relationships of *Trilophosaurus*." By JOSEPH T. GREGORY. Pp. 273–360; pls. 16; figs. 11. $0.80 separately.

Trilophosaurus buettneri Case was described from a fragment of dentary in 1928 and referred to the Cotylosauria on the basis of the transversely broad teeth which resemble somewhat those of *Diadectes* and *Procolophon*. Extensive quarrying in Howard County, Texas, has yielded a large amount of well-preserved skeletal remains of this genus. The osteology of *Trilophosaurus* is described in great detail, principally on the basis of a nearly complete skeleton. All important osteological details are figured in well-executed text figures and plates. Through this paper *Trilophosaurus* becomes one of the best-known genera of Upper Triassic reptiles.

The skull of *T. buettneri* has a temporal fenestra bounded dorsally by the parietal, posteriorly and laterally by the squamosal, and anteriorly by the postfrontal. Gregory believes that the postorbital extends into the boundary but indicates that the sutures are not sufficiently well shown to be definitive. The fenestra seems to be homologous to the superior temporal fenestra of the Sauropterygia and the Protorosauria and is one of the principal criteria for reference of *Trilophosaurus* to the Protorosauria as proposed in this paper. Other features of the skull and the skeleton confirm this assignment. The new family Trilophosauridae is erected to include the reptile.

The second section of the paper is devoted to an extensive comparison of *Trilophosaurus* with representatives of all major reptilian groups. This is followed by a short discussion of the appearance and habits of the animal. In the final pages a short summary and a complete series of measurements are included. The paper is an important contribution to our knowledge of Triassic reptiles inasmuch as it gives one of the few truly adequate descriptions of a member of the order Protorosauria.

6. "Amphibians from the Dockum Triassic of Howard County, Texas." By H. J. SAWIN. Pp. 361–99; figs. 12; tables 3. $0.25 separately.

This paper is devoted largely to a detailed description of the skull and skeleton of a new species of Dockum stereospondylous amphibian, *Buettneria howardensis* Sawin. The relationships of the species of *Buettneria* and other North American members of the family Metoposauridae are considered in the concluding discussion. Extensive comparisons are contained in comparative tables. The paper adds important details to the knowledge of the genus *Buettneria*, but its most important contribution lies in the badly needed comparative studies.

7. "Decapod Crustaceans from the Cretaceous of Texas." By H. B. STENZEL. Pp. 401–76; pls. 1; figs. 26; tables 2. $0.70 separately.

This paper describes thirty-one species (twenty-one new and one not specifically identified) referred to twelve genera (one new) in nine families. Several of these species are represented by unusually abundant and perfect specimens. There is much new information on relationships, and many details of previously imperfectly known forms are added. An introductory section is devoted to some features of comparative anatomy and stratigraphic ranges of genera, both in Texas and elsewhere, which are tabulated.

8. "An *Amebelodon* Jaw from the Texas Panhandle." By J. T. Gregory. Pp. 477–82; pls. 1; figs. 1. $0.05 separately.

This paper is concerned with the description of an excellently preserved lower jaw of *Amebelodon fricki* and a discussion of the relationships of the genus in which is included a redefinition of the subfamily Amebelodontinae. Dentinal rods have been found by Gregory in a newly described specimen, although they were not observed in the holotype. This, in addition to other evidence, has convinced Gregory that there is no reason for considering the Platybelodontinae and Amebelodontinae, the shoveltusked mastodonts, to be distinct. He questions seriously the complex classification of Osborn which recognizes three families and eleven subfamilies among the trilophodont type of mastodons. The redefinition of the subfamily Amebelodontinae is clear and defines in concise terms the limits of the group. In discussion of *Platybelodon*, *Torynobelodon* is referred to the genus *Platybelodon*. *Phioma* is regarded as not belonging to the subfamily Amebelodontinae.

9. "Quaternary of the Texas High Plains." By GLEN L. EVANS and GRAYSON E. MEADE. Pp. 485–507; pls. 1; figs. 9. $0.15.

Evans and Meade have made extensive studies of the surface deposits of the Texas

High Plains and have here given an excellent report of their findings and interpretations. The general setting is laid by a brief description of the topography and drainage of the Texas High Plains. Three types of deposits are taken up successively: (1) lake or pond deposits, (2) stream-valley deposits, and (3) wind deposits. The final section of the paper lists the Pleistocene vertebrate localities.

The descriptions and discussion of the lake, or playa, deposits are most detailed and most interesting. Many of the local beds of Blancan and more recent age are shown to be of this type. The origin of the basins of deposition is treated at some length. Subsidence, considered the prime factor by some earlier students, is thought to be of minor importance, and deflation during stages of aridity is indicated as the chief agent producing the basins. The lake deposits appear to have been formed during stages of humid climate. The climate implications of this study are of considerable significance, especially for the relationships of these deposits far from the glaciers and those made at the margins and under the continental ice sheets. Evidence is advanced to show that the Blanco beds are of Nebraskan age. Tule and Spring Creek deposits are considered Middle Pleistocene and the Tahoka clay Wisconsin in age.

Stream and eolian deposits are treated more briefly. It is pointed out that the stream history appears to be closely correlated with climatic cycles and reveals climatic phenomena similar to those shown by the playas. The paper has two important functions: It gives an excellent factual account of the recent geology of the High Plains of Texas and it presents new and interesting interpretations which suggest means of correlating the events of the region with those of other areas of Pleistocene deposition and erosion.

10. "The Blanco Fauna." By GRAYSON E. MEADE. Pp. 509–42; pls. 9; figs. 4. $0.50.

This report is primarily descriptions of an extensive fauna from the Blanco beds in Crosby County, Texas, but it also includes pertinent comments upon the stratigraphic position of the fauna, the nature of its occurrence, and the origin of the Blanco beds. The fauna includes nearly all known members previously described plus seven genera not known from the Blanco heretofore. The locality from which the vertebrates were obtained is described in detail. Meade offers interpretations of the fauna and deposits which contrast markedly with those of various previous students. He believes that the fauna and the nature of the beds, particularly the features indicating climatic conditions during deposition, demonstrate that the Blanco represents a single stage in opposition to Osborn's interpretation of several stages and that the age of the beds is Lower Pleistocene rather than Upper Pliocene. The beds are interpreted as lacustrine rather than as fluviatile, as thought by Matthews.

The descriptions of the members of the fauna are clear, and important specimens are illustrated in the plates. Tables of comparative measurements are included for many of the important groups of vertebrates. This paper adds materially to the knowledge of the Blanco fauna and is challenging in its new interpretations. It should form an excellent basis for comparing the faunas from the Blanco beds with those from other Blancan deposits in North America.

This volume, devoted entirely to the results of strictly scientific research, is effective testimony to the extraordinarily rich and diverse paleontological resources of Texas. It was planned by Dr. E. H. Sellards, former director of the Texas Bureau of Economic Geology, before his retirement. Although it has no direct bearing on economic geology, as that is usually understood, some of these researches will undoubtedly find practical application in the solution of economic problems. Also, these papers are important and permanent additions to essential geological science and are bound to be remembered and consulted long after most contemporary publications on economic subjects have lost their usefulness.

J. MARVIN WELLER
EVERETT C. OLSON

Pennsylvanian Ostracodes of Illinois. By CHALMER L. COOPER. (*Ill. Geol. Surv. Bull. 70.*) Urbana, Ill., 1946. Pp. 177; pls. 21. $1.00.

Cooper's well-illustrated report is the most extensive survey as yet published of the Pennsylvanian ostracodes of this country, covering Morrow to Wabaunsee faunas. Included is a concise stratigraphic summary by J. Marvin Weller of the Pennsylvanian sequence in Illinois, emphasizing the numerous still unsolved problems of correlation. Most of these relate to beds above the Shoal Creek limestone which

would correlate with strata of the Missouri and Virgil series and which occur in scattered outcrops isolated by glacial drift.

In Illinois "ostracodes commonly occur in the upper or marine members of the cyclotherm," although "zones in the underclay limestones and associated beds yield distinctive" faunas commonly considered fresh-water in origin. At least one of the included fresh-water species occurs in the Permian of Kansas. Cooper's discussion of the many zonally restricted species greatly enhances the value of ostracodes as index fossils, even though these short-lived forms are somewhat outnumbered by more hardy species. The early faunas are easily recognized, and few Morrow or Atoka species occur in formations younger than Des Moines. The faunas of the Des Moines series are more like the younger faunas than the older ones. The Missouri series combines species known from either earlier or later strata although a few species are restricted; and the Virgil series combines many short-lived species with older, very hardy, species, many of which continue into the Permian, as well as with a few new species which also continue into Permian strata. The western series and group names have not been adopted in Illinois but were merely used "to conveniently compare Illinois strata with those of the Mid-continent region."

This study shows that most of the Pennsylvanian genera are now well known; of the forty-seven genera found in Illinois only three are new, and few genera are placed in synonomy. Some genera are, however, not yet well established or understood. Cooper believes *Harltonella* Bradfield congeneric with *Waylandella* Coryell and Billings, but the thick downward projecting ridges at the postventral angles of *Harltonella* are very different from the backward projecting spines of *Waylandella*. Instead, *Hartonella* is close to *Coryellites* Kellett, which has not only the same overlap but also the same beaklike ridge on the larger valve. This diagnostic ridge was evidently overlooked by Cooper, for he nowhere mentions it and unfortunately refers to *Coryellites* a number of unornamented species with well-defined dorsal overlap. As for the genus *Carbonita*, Cooper does not follow Scott in referring the Illinois species to the living fresh-water genus *Cypridopsis;* since he is probably correct in retaining the name *Carbonita*, his reasons would have been helpful in a final settlement of this question. Species referred to another living genus, *Candona*, seem to lack the specialized hinge margin of the type species, although possibly they are related to some of the various forms referred to that large and loosely knit genus. The genus *Ectodemites* Cooper seems unacceptable, being founded on a molt of one of the species most closely related to *Amphissites rugosus* Girty, the type of the genus *Amphissites;* furthermore, there seems to be no reason for generically differentiating such forms as *Ectodemites plummeri* Cooper (Pl. XV, Figs. 37–42) and *Amphissites congruens* Cooper (Fig. 43). The synonomy of the often misinterpreted genus *Jonesina*, founded on a European species, has been very unsettled lately, and Johnson's study of type material has been generally overlooked. Recognizing that *J. bolliaformis* is not a true *Jonesina*, Cooper placed it in the genus *Sansabella*. However, near the Wolfcamp-Leonard boundary in northern Texas this species develops the ridges characteristic of *Knoxina* Coryell and Rogatz and should be referred to that genus along with the ancestral Mississippian *Geffienites*.

It is difficult to understand Cooper's denial that the youngiellid type of hingement is present in the genus *Moorites* and in the McAlester *Youngiella* described by Wilson, in view of Wilson's statement that the McAlester species are crenulate and that both he and Knight had observed the minute teeth and sockets extending all along the hinge of *Moorites minutus*, the type species of *Moorites*.

In the past, far too many Pennsylvanian species have been proposed because of failure to recognize immature molts and to make allowance for individual and sexual variation. As a specific character the form-ratio still seems overstressed in this report, especially in the small, plain genera like *Bythocypris*. It is known that in certain living genera, *Loxoconcha*, for example, the male is much more elongate than the female. Cooper's synonymies reduce the number of Pennsylvanian species; but, except for the Bradfield and Payne faunas, we are left in the dark as to whether or not his conclusions are based on the study of type material. Certain conclusions suggest the lack of firsthand knowledge, as in the case of Upson's Funston limestone *Hollinella*, which is removed from the Permian species *H. emaciata* and referred to the Shawnee *H. cushmani*, thus extending the range of the latter well into the Permian. Cooper identifies a Cherokee form with the Shawnee-Wabaunsee *Cavellina fittsi* because of a curved ridge on both which, as he notes, is similar to the ridge

found on the young of many species of *Cavellina*. This ridge, inherited from the ancestral Devonian *Eocytherella*, is much shorter on the Upper Pennsylvanian *C. fittsi* and is found only on very immature specimens not much more than .6-mm. long, as contrasted to the ridged Cherokee forms 1.2-mm. long.

One of the most interesting suggestions made by Cooper, possibly important because bearing on the troublesome question of the orientation of all beyrichias, is that the narrow-frilled hollinellas, being the largest, are females. Usually, it has been assumed that the wide-frilled individuals of this group, forms with the so-called "brood pouch," are the females.

BETTY KELLETT NADEAU

The Journal of Glaciology. Vol. I, No. 1 (January, 1947). Kensington Gore, London, S.W. 7: British Glaciological Society. Pp. 42. 7*s*. 6*d*. per copy.

The British Glaciological Society, founded in 1945, has recently issued the first number of a new scientific magazine—the *Journal of Glaciology*. This new journal is to serve both as the official organ of the Society in the dissemination of glaciologic knowledge and as a general forum for interchange of ideas among students of snow and ice. Its editorial committee consists of Gerald Seligman, president of the Society, Launcelot Fleming, Brian Roberts, and Robert Moss. The new venture seems a timely one, particularly in view of the rapidly growing interest in Arctic and Antarctic regions, which are now becoming far more accessible and important to us than formerly.

This inaugural number contains the proceedings of the Society, several papers presented at its general meetings, various summaries of progress in researches, correspondence, notes, and a bibliography of glaciological literature since 1937. A surprising amount of diverse, vital information is packed within this single issue.

The *Journal of Geology* congratulates the *Journal of Glaciology* on its auspicious start and welcomes it as a promising new member of the geologic fold.

R. T. C.

"Report of the Committee on Marine Ecology as Related to Paleontology," No. 6, 1945–1946. By HARRY S. LADD, Chairman. Division of Geology and Geography, National Research Council, 1946. Pp. 101 (mimeographed). $0.50.

The material presented in this report is of four types: (1) the outline of a proposed treatise on marine ecology and paleontology, (2) announcements of current activities, (3) bibliographic lists, and (4) papers on marine and paleoecology.

The planned treatise is certain to be of great interest to all paleontologists and stratigraphers, and a real opportunity exists to make a major contribution in this field. The best English work on this subject is *Ecological Animal Geography* by Richard Hesse, translated and revised by W. C. Allee and K. P. Schmidt (New York: Wiley, 1937), but this was written for zoölogists, and a somewhat different approach and considerable change in emphasis are required to present the subject matter so that it will have maximum application to paleontology and geology. A work of this type is urgently needed to direct paleontologists' attention to the importance of ecology and to encourage the gathering and recording of pertinent data which are all too commonly overlooked.

As planned, the treatise will consist of two parts, each with an annotated bibliography. The first part will be concerned with marine ecology, presumably largely based on the relations of Recent organisms to their environments. The second part will consist of a series of analyses of selected outstanding regions, one for each period, rather than an attempt to interpret the entire past of all the earth.

The committee desires interested and qualified persons to volunteer their services in the preparation of the various sections. The committee intends to synthesize all contributions into a unified whole so that the volume will not be simply a collection of papers, and individual authorship will not be acknowledged except by the inclusion of a list of contributors in the committee. This plan will work advantageously for the first part, but in my opinion the analyses which will make up the second part should appear under their authors' names, because interpretations of this kind are so subjective that it is important to know who has made them.

The section on current activities is very brief, and only sixteen projects are listed. Observations at Bikini are given by far the greatest emphasis.

About eighty recently published papers are listed—some are briefly annotated. They are partly grouped according to the principal types of organisms. Many of them are concerned with ecology only to a very minor degree.

Three additional bibliographies list (1) Japanese publications that appeared during the war—about forty titles, mostly well abstracted; (2) articles dealing with invertebrate faunas of the Pacific—over one hundred titles, half of them published prior to 1925, mostly briefly annotated; and (3) articles on ecology and paleoecology of New Zealand—about twenty titles dating back to 1913, mostly annotated and some extensively abstracted.

The last section consists of five papers: (1) "Paleoecology in Western Australia," by Curt Teichert; (2) "Methods of Study of Recent Foraminifera," by Fred B. Phleger, Jr.; (3) "Fish Remains in Recent Deposits," by Lore Rose David; (4) "Distribution of Organisms at the Mouth of Wakasa Bay, Japan Sea and Adjoining Continental Shelf," by Hiroshi Niino; and (5) "Life and Environment of the Early Ordovician Sea in Central Texas," by Preston Cloud and Virgil Barnes.

The last paper is by far the most interesting. It is an excellent example of thoughtful and convincing imagination in which past conditions are re-created on the basis of geologic evidence and analogy. Presumably this is the type of interpretation that is desired for the second part of the treatise; and, if other sections can be secured at as satisfyingly high a standard, a most noteworthy result will have been achieved. The reasoning is sound and the conclusions are logical, but an experienced geologist will probably realize that most, if not all, of the observed facts might be interpreted differently. This is not an adverse criticism of the paper but only a warning that our knowledge is so imperfect that few positive conclusions of more than reasonable certainty can be drawn. Much more work of this type is needed, and in time the accumulation of ideas and the testing of theories will lead closer to the results we all desire.

J. MARVIN WELLER

Pennsylvanian Geology of a Part of the Southern Appalachian Coal Field. By HAROLD R. WANLESS. (Geological Society of America Memoir 13, 1946.) Pp. 162; pls. 40.

This volume reports a continuation of Wanless' extensive Pennsylvanian stratigraphic studies that have been described in numerous previous publications, including *Pennsylvanian Correlations in the Eastern Interior and Appalachian Coal Fields* (Geol. Soc. Amer. Special Paper 17). In many ways it is an outgrowth of his northern Appalachian studies. Together with Special Paper 17 it constitutes a more comprehensive description of an important part of the Appalachian Coal Measures than any publication to appear since J. J. Stevenson's "Carboniferous of the Appalachian Basin" (*Bull. Geol. Soc. Amer.*, 1904–6). Although the field work was of reconnaissance nature, Wanless' previous experience; his thorough knowledge of the literature; his painstaking and minute examination of more than four hundred selected stratigraphic sections, some more than 2,000 feet thick, and his application of recent discoveries and modern ideas to the problems of correlation have resulted in a remarkably clear and concise exposition of a very complex succession of strata, reaching a maximum thickness of about 6,000 feet, and their variations throughout an area of more than 7,500 square miles. There can be no doubt that he has brought a great measure of order to a region formerly complicated by at least six different local and unrelated systems of nomenclature and classification. He presents a single group of stratigraphic names and a general classification which is a modification and combination of two Tennessee systems as a framework for his observations but makes no plea for its general adoption.

The major structural features of the southern Appalachian basin are briefly described and shown on a map at the scale of 15 miles to 1 inch; the principal publications dealing with the area are listed; the main stratigraphic subdivisions are described, traced, and correlated; Pennsylvanian deposition is discussed; important unsolved problems are pointed out; and a very complete glossary of stratigraphic names is presented.

Considerably less than one-half of the report consists of ordinary stratigraphic descriptions, and nearly as much space is devoted to the detailed measurements of pertinent portions of more than thirty-five selected stratigraphic sections which illustrate the characteristic features of all but the persistently massive sandstone formations. By far the greater part of Wanless' observations are presented in the form of twenty charts, which show the correlations of a large number of graphic columnar sections, mostly based upon original field measurements. Some of

these correlated sections extend parallel to the structure, and others cut across it at intervals of about 35 miles. The columns are at a scale of about 135 feet to 1 inch and show all principal types of lithology and fossil zones distinguished as bearing marine, brackish, and fresh-water invertebrates and land plants. Each chart is explained and discussed in about a page of fine type. An enormous amount of information is thus compressed into a very modest space.

The Pennsylvanian strata in this region are of Pottsville and early Allegheny age. They are divided into two groups: the Lee, which corresponds to the Pocahontas and New River groups of West Virginia, and a younger unnamed group including beds younger than Kanawha only in the higher mountains of the northern part of the region. Each is separated into several formations ranging in maximum thickness from 100 to 1,800 feet. The Lee formations consist of prominent, massive, conglomeratic sandstones and alternating units of less resistant and more or less shaly strata. Younger formations are heterogeneous units not based on a similar alternation of lithology. Sandstones included in them are generally finer grained and more micaceous than those of the Lee, and they are rarely conglomeratic. Such differences in sandstones and the restriction of a particular type of dark shale to the Lower and Middle Pottsville is widely characteristic and has been noted as far west as Oklahoma.

The cyclical repetition of strata recognized in this region differs from the familiar Illinois type of cyclothem by its greater proportion of coarser clastics which recur in several zones, the occurrence of several coals that may be splits from a single seam, and the rare development of strata with typically marine faunas. Invertebrate fossils, however, were found at a surprisingly large number of places, but most of them suggest brackish or nearly fresh-water conditions. All these differences might be expected in a region of adequate sedimentation close to the source area. Wanless believes that most of the sediment was derived from the old Appalachian land mass, although he recognizes that a smaller part may have been brought in from the Canadian shield.

Stratigraphic correlations substantiate the conclusion, previously based on paleobotanical studies, that the Pottsville section thickens greatly southward from Kentucky. Wanless' correlations, however, demonstrate some formerly unknown details of this thickening which is most notable in the neighborhood of several anticlines and fault zones. Apparently the rate of downwarping in the Pennsylvanian geosynclinal basin differed importantly on either side of these critical zones which became the axes of structural deformation when the region was compressed at the end of the Paleozoic era. His correlations also show the overlap of younger Lee strata onto the Mississippian, westward toward the Nashville dome.

The glossary of about two hundred and fifty stratigraphic names, mostly names of coal seams, is particularly useful because coal-seam terminology was omitted from Wilmarth's *Lexicon*. The type locality (with reference) of each named unit is given, its stratigraphic position is stated, and it is correlated with units known by other names. Also, each is indexed to the text and plates.

The report is illustrated by seventeen plates of excellent photographs and by several formal correlation charts.

J. Marvin Weller

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SYMPOSIUM ON PENNSYLVANIAN PROBLEMS

HAROLD R. WANLESS
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Morning and afternoon sessions of Section E (Geology and Geography) of the American Association for the Advancement of Science at St. Louis, Missouri, on March 27, 1946, were devoted to a symposium on the Pennsylvanian. The following papers were presented:

Introduction to Symposium on Pennsylvanian Problems, HAROLD R. WANLESS, University of Illinois, Urbana.

Summary of Classification of the Pennsylvanian Formations of Texas, with Special Reference to the Lower Pennsylvanian of the Llano Region, FREDERICK B. PLUMMER, University of Texas, Austin.

Pennsylvanian Classification and Correlation Problems in North-central Texas, M. G. CHENEY, Anzac Oil Corporation, Coleman, Texas.

Distribution and Correlation of Pennsylvanian Rocks in Late Paleozoic Sedimentary Basins of Northern New Mexico, CHARLES B. READ and GORDON H. WOOD, U.S. Geological Survey, Albuquerque, New Mexico.

Regional Variations in Pennsylvanian Lithology, HAROLD R. WANLESS, University of Illinois, Urbana.

Invertebrates in Pennsylvanian Correlations, J. MARVIN WELLER, University of Chicago, Chicago.

Role of Microfossils in Interregional Pennsylvanian Correlations, CHALMER L. COOPER, Illinois State Geological Survey, Urbana.

Pennsylvanian Floral Zones and Floral Provinces, CHARLES B. READ, U.S. Geological Survey, Urbana.

Plant Microfossils in Correlation of Coal Beds, ROBERT M. KOSANKE, Illinois State Geological Survey, Urbana.

Spore Floras of the Pennsylvanian of West Virginia and Kentucky, AUREAL T. CROSS, University of Cincinnati, Cincinnati, Ohio.

These papers have been assembled for publication, in the hope that they will be thus more useful to geologists working with Pennsylvanian problems.

INTRODUCTION TO SYMPOSIUM ON PENNSYLVANIAN PROBLEMS

HAROLD R. WANLESS
University of Illinois

Because of their valuable resources of coal, oil, and gas, refractory clays and other ceramic materials, iron ores and other industrial materials; their widespread distribution in the United States; their richly preserved record of the plant and animal life of the period; and their lithologic complexity and variability, Pennsylvanian rocks have been the subjects of many research projects. The "Lexicon of Geologic Names of the United States"[1] records about fourteen hundred names which have been applied to Pennsylvanian units, and this list does not include coal beds, to which at least one thousand additional geographic names have been applied. Two valuable summaries of Pennsylvanian classifications and correlations have recently been published, one representing the co-operative results of a Pennsylvanian subcommittee of the Stratigraphic Committee of the National Research Council, headed by Dr. Raymond C. Moore,[2] and the other a committee of the American Association of Petroleum Geologists, headed by Dr. Monroe Cheney.[3] One might suppose that there would be no necessity for additional programs, such as the present one, on the problems of the Pennsylvanian; but there are still many uncertainties as to correlations in much-studied areas; there are numerous areas, especially in the western states, in which the Pennsylvanian succession is imperfectly known and lumped into thick heterogeneous formations; and many well-represented groups of fossils await detailed study. With the return of peace, many geologists will be able again to turn their attention to such studies as these, and a new generation of college undergraduates and graduate students will be seeking problems suitable for thesis investigations.

The present program has been prepared with the intent of appraising the present state of our understanding of problems and especially to seek out and direct attention to poorly understood areas and to new and promising methods of approach to old problems and groups of fossils, whose detailed study may be expected to contribute to the better understanding of the correlation of, or environments of origin of, certain Pennsylvanian rocks. It was hoped that the chairmen of both committees which have recently worked on Pennsylvanian problems might participate in the program, but Doctor Moore's present brief absence from the country has made it impossible to present a paper he was to give on "Principles of Classification Applied to the Pennsylvanian," an important subject on which complete agreement has not been reached among the principal

[1] M. Grace Wilmarth, *U.S. Geol. Surv. Bull. 898* (1939).

[2] R. C. Moore and others, "Correlation of Pennsylvanian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), pp. 657–706.

[3] Association Subcommittee on Carboniferous, M. G. Cheney, chairman, "Classification of Mississippian and Pennsylvanian Rocks of North America," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIX (1945), pp. 125–69.

students. Dr. Cheney is able to participate in the program, even though he is charged with directing the annual convention of the Association of Petroleum Geologists.

STAGE OF ADVANCEMENT OF REGIONAL STRATIGRAPHIC STUDIES

Little recent study has been made of the Narragansett coal basin, and its relations to other Pennsylvanian areas are poorly understood. It probably resembles in succession and lithology the Maritime Provinces of Canada more than it does other areas in the United States. If any of the metamorphic series of New England which are mapped as Carboniferous are of Pennsylvanian age, their exact age and relations to other unmetamorphosed successions remain to be worked out.

Further detailed studies of the anthracite fields, especially by paleobotanists, are desirable. There are great changes in thickness and facies between the southern and the northern anthracite basins, which, while known, are imperfectly understood. The southern field seems to have a thick Lower and Middle Pottsville section but no Upper Pottsville, while the northern field seems to have a thin Upper Pottsville or Kanawha section but no Middle or Lower Pottsville beds.

Although the type section of the Pennsylvanian is in Pennsylvania, G. H. Ashley[4] and B. Coleman Renick[5] have recently called attention to errors in correlation between Beaver and Allegheny valleys affecting the boundaries of the type Allegheny formation or group and have suggested moving up the basal Allegheny boundary to the base of the Kittanning sandstone.

In Ohio detailed published studies cover only about eight counties—Columbiana and Jefferson in the northern part of the state; Muskingum near the center; and Vinton, Jackson, Scioto, Pike, and Lawrence in southern Ohio. Stratigraphic and faunal studies have been published for the Pottsville[6] and Conemaugh[7] formations. Dr. G. W. White is engaged in studies of the Monongahela of Ohio, and studies of the Allegheny have also been undertaken by M. T. Sturgeon.

In West Virginia and Virginia large county reports cover each county of the Pennsylvanian area, and in West Virginia most beds of a long and very heterogeneous succession have been named. A new contribution to the Pennsylvanian of West Virginia, the succession of spore microfloras by Dr. A. T. Cross, is part of this program. The detailed succession of the early Pennsylvanian underlying the deeper part of the Dunkard Basin is not well described.

The geology of the Maryland Pennsylvanian is well documented in studies published by the Maryland Survey, especially by Dr. C. K. Swartz.

The published literature on the eastern Kentucky coal field is devoted mostly to the tracing of the minable coals, with one paleontologic paper by W. C. Morse.[8] Uniformity in nomenclature between the several river valleys has

[4] "The Pittsburgh-Pottsville Boundary," *Jour. Geol.*, Vol. LIII (1945), pp. 374–89.

[5] "Correlation of the Lower Allegheny–Pottsville Section in Western Pennsylvania," *Jour. Geol.*, Vol. XXXII (1924), pp. 64–80.

[6] Helen Morningstar, "Pottsville Faunas of Ohio," *Ohio Geol. Surv., Bull. 25* (4th ser., 1922).

[7] D. D. Condit, "Conemaugh Formation in Ohio," *Ohio Geol. Surv., Bull. 17* (4th ser., 1912).

[8] "The Pennsylvanian Invertebrate Fauna of Kentucky," *Ky. Geol. Surv.*, Vol. XXXVI (6th ser., 1931), pp. 295–349.

not been attained, and most of the strata between the minable coals have not been named. Data on the unexposed lower Pennsylvanian of the deeper part of the eastern Kentucky field come mostly from inadequate drillers' logs of oil wells. The manner of northwestward and northward thinning and disappearance of the valuable Pocahontas and New River coals is imperfectly known, both in Kentucky and in West Virginia.

A study by the author of the Tennessee coal field, in which its strata are correlated with those in Kentucky, Virginia, and Georgia has recently been published.[9] The faunas of the Pennsylvanian of the southern Appalachian field have been given rather scant attention. Dr. C. H. Summerson[10] has found more than two hundred species of invertebrates in outcrops in West Virginia, Kentucky, and Tennessee. This fauna includes, in addition to the common groups of macrofossils, abundant ostracodes and some foraminifera, conodonts, and holothurians. Fresh-water ostracodes and pelecypods are noteworthy features of the faunas studied by him. A short paper by M. L. Thompson[11] on Ohio material represents all the fusulinid work done in the Appalachian coal field.

The small coal field of northwestern Georgia has been matched quite well with that of adjacent southern Tennessee. Little has been done recently with the Pennsylvanian of Alabama. Different sets of names are applied to coals of the Warrior,[12] Cahaba,[13] and Coosa[14] coal fields, which are in separate fault blocks; and none has been adequately traced across the comparatively barren Plateau coal fields of northeastern Alabama to tie in with the southern Tennessee coal field to the north. Marine faunas are known to exist but are undescribed. Little or nothing is known as to the character of the subsurface Pennsylvanian succession which connects the Alabama fields with those of Arkansas across Mississippi and eastern Arkansas.

In western Kentucky there are too many systems of names initiated in connection with studies of separate quadrangles, and the coals are largely known by numbers not consistently applied to the same coals in different parts of the field and differing from the numbers applied to the same coals in the adjacent Illinois and Indiana fields.

The Indiana field is extensively covered in old volumes by Ashley and his associates, but much new detail about subsurface Pennsylvanian resulting from core drilling for coal or for oil structures has not been assimilated and published. D. W. Franklin[15] has recently published a section for part of southern Indiana, naming several marine limestones which had not previously been differentiated.

Detailed studies of the Pennsylvanian in Illinois are well advanced. The coal division of the Illinois State Geological Survey has for several years collected

[9] "Pennsylvanian Geology of a Part of the Southern Appalachian Coal Field," *Geol. Soc. Amer. Mem. 13* (1946).

[10] "Some Pennsylvanian Faunas of Tennessee, Eastern Kentucky, and West Virginia" (unpublished Ph.D. thesis, University of Illinois, 1942).

[11] "Pennsylvanian Fusulinids from Ohio," *Jour. Paleon.*, Vol. X (1936), pp. 673–83.

[12] Henry McCalley, "Report on the Warrior Coal Basin," *Ala. Geol. Surv.* (1900).

[13] Joseph Squire, "Report on the Cahaba Coal Field," *Ala. Geol. Surv.* (1890).

[14] A. M. Gibson, "Report upon the Coosa Coal Field," *Ala. Geol. Surv.* (1895).

[15] "Pennsylvanian Stratigraphy of Part of Southern Indiana," *Trans. Ill. Acad. Sci.*, Vol. XXXVI (1944), pp. 85–92.

samples at 1–5-foot intervals from drilling oil tests taken by members of its staff and correlated with drilling-time logs and electric logs. The results have been a vastly increased knowledge of the Middle and Lower Pennsylvanian, where these are buried in the deeper part of the basin.[16] There remains uncertainty as to the relations of the youngest Pennsylvanian in some parts of the Illinois Basin, the position corresponding to the Missouri-Virgil boundary, and the correlation of the isolated high Pennsylvanian rocks of Webster and Union counties in western Kentucky, south of the Rough Creek fault, with the Illinois section.

In Michigan, where the Pennsylvanian covers a large area but is deeply buried by glacial drift, detailed studies by W. A. Kelly[17] of the one small area of good outcrops have been published. The age, lithology, and succession of most of the Michigan Basin Pennsylvanian are, however, poorly known.

Recent detailed studies by Lewis M. Cline and others in Iowa have resulted in tracing numerous thin marker beds of the Upper Des Moines and Lower Missouri groups south across Missouri to eastern Kansas[18] and eastward to tie in with the Illinois section.[19] The higher Missourian beds[20] remain to be matched with beds in Illinois, and strata of Lampasas and Morrow age, if any, have not yet been worked out.

In Missouri the outcropping Pennsylvanian strata have been carefully traced by H. Hinds and F. C. Greene[21] and by others to tie in with both Iowa and Kansas successions. The thickened Lower Pennsylvanian subsurface section of the Forest City Basin has not been so accurately subdivided. Although well described from several diamond-drill records,[22] the Lampasas–Des Moines boundary remains somewhat uncertain.

G. E. Condra[23] has subdivided the outcropping Upper Pennsylvanian of Nebraska about as minutely as has been done anywhere. Six to eight named beds may appear in the photograph of a single outcrop. The subsurface Lower Pennsylvanian, however, awaits further detailed study and differentiation. The lithologic changes under the Great Plains between the exposed sections of eastern Kansas and Nebraska and the western exposures in the Black Hills, eastern Wyoming, and Colorado are imperfectly known. Condra's zonation of the beds of the Hartville Uplift, Wyoming,[24] and its correla-

[16] Earle F. Taylor, M. W. Pullen, Paul K. Sims, and J. Norman Payne, "Methods of Subsurface Study of the Pennsylvanian Strata Encountered in Rotary-Drill Holes," *Ill. Geol. Surv., Rept. Investigations No. 93* (1944), pp. 9–21.

[17] "Pennsylvanian Stratigraphy near Grand Ledge, Michigan," *Jour. Geol.*, Vol. XLI (1933), pp. 79–86.

[18] "Traverse of Upper Des Moines and Lower Missouri Series from Jackson County, Missouri, to Appanoose County, Iowa," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXV (1941), pp. 23–72.

[19] J. M. Weller, H. R. Wanless, L. M. Cline, and D. G. Stookey, "Interbasin Pennsylvanian Correlations, Illinois and Iowa," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXVI (1942), pp. 1585–93.

[20] G. E. Condra and J. E. Upp, "The Middle River Traverse of Iowa," *Neb. Geol. Surv., Paper No. 4* (1933).

[21] "The Stratigraphy of the Pennsylvanian Series in Missouri," *Mo. Bur. Geol. and Mines*, Vol. XIII (2d ser., 1915).

[22] H. S. McQueen and F. C. Greene, "The Geology of Northwestern Missouri," *Mo. Geol. Surv. and Water Resources*, Vol. XXV (2d ser., 1938), pp. 120–24, 169–76.

[23] "The Stratigraphy of the Pennsylvanian System in Nebraska," *Neb. Geol. Surv., Bull. 1* (2d ser., 1927); "Correlation of the Pennsylvanian Beds in the Platte and Jones Point Sections of Nebraska," *Neb. Geol. Surv., Bull. 3* (2d ser., 1930).

[24] G. E. Condra and E. C. Reed, "The Permo-Pennsylvanian Section of the Hartville Area of Wyoming," *Neb. Geol. Surv., Paper 9* (1935).

tion with the mid-continent section is the most noteworthy such study up to the present.

The Pennsylvanian of Kansas is probably as well known as that of any area in the country.[25] Because of the presence there of both marine invertebrates and plant fossils well distributed throughout the column, Moore has proposed that the Kansas section be considered the standard Pennsylvanian succession of this continent, since the section in Pennsylvania does not afford a complete record of the succession of marine faunas.

In Oklahoma there is an abundance of information,[26] but the great changes in thickness and facies between northeastern Oklahoma[27] and the McAlester,[28] Ouachita,[29] Ardmore,[30] and Anadarko basins[31] will, no doubt, furnish grounds for research and difference of opinion for years to come. Dr. Cheney is contributing to the stratigraphy of the subsurface Pennsylvanian of Oklahoma and Texas basins in another paper in this symposium.

The Pennsylvanian of Arkansas varies from a thin northern Ozark facies to a tremendously thick southern Ouachita facies and offers problems similar to those of Oklahoma; but, with scantier marine faunas and less detailed study, these problems are less well understood.[32] There has been much difference of opinion as to the position of the Pennsylvanian-Mississippian boundary in Oklahoma and Arkansas, where the Jackfork, Stanley, and Springer formations have been variously interpreted.[33] Similar uncertainty exists with respect to the Parkwood of Alabama; the lower Pocahontas, Bluestone, and Princeton of West Virginia; some "transition" beds of the southern anthracite field; and the Amsden and perhaps other formations of the Rocky Mountains. It seems probable that along the southeastern and southern borders of the Appalachian and Ouachita geosynclines and in some parts of the Rocky Mountains deposition was nearly continuous from the Mississippian into the Pennsylvanian.

In Texas the outcropping Pennsylvanian of central and north-central Texas is well known from studies by F. B. Plummer and R. C. Moore[34] and by others. Dr. M. G. Cheney has worked

[25] R. C. Moore, "Stratigraphic Classification of Pennsylvanian Rocks of Kansas," *Kan. Univ. Bull. 22* (1935); John M. Jewett, "Classification of the Marmaton Group, Pennsylvanian, in Kansas," *Univ. Kan. Pub., Kan. Geol. Surv. Bull. 38*, Part XI (1941); and many other titles.

[26] Robert H. Dott, "Regional Stratigraphy of Mid-continent," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXV (1941), pp. 1660–80.

[27] R. C. Moore, "Upper Carboniferous Rocks of Southeastern Kansas and Northeastern Oklahoma," *Kan. Geol. Soc., Guidebook, 11th Ann. Field Conf.* (1937), pp. 9–16.

[28] Thomas A. Hendricks, "Geology and Fuels Resources of the Southern Part of the Oklahoma Coal Field. I. The McAlester District, Pittsburg, Atoka, and Latimer Counties," *U.S. Geol. Surv. Bull. 874-A* (1937).

[29] H. D. Miser, "Carboniferous Rocks of the Ouachita Mountains," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XVIII (1934), pp. 971–1099.

[30] C. W. Tomlinson, "The Pennsylvanian System in the Ardmore Basin," *Okla. Geol. Surv. Bull. 46* (1929).

[31] W. B. Boyd, "Deepest Well in Mid-continent Region, Washita County, Oklahoma," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIV (1940), pp. 735–38.

[32] T. A. Hendricks and C. B. Read, "Correlations of Pennsylvanian Strata in Arkansas and Oklahoma Coal Fields," *Bull. Amer. Assoc: Pet. Geol.*, Vol. XVIII (1934), pp. 1050–58.

[33] David White, "Age of Jackfork and Stanley Formations of Ouachita Geosyncline, Arkansas and Oklahoma, as Indicated by Plants," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XVIII (1934), pp. 1010–17; Chalmer L. Cooper, "Age Relations of Stanley and Jackfork Formations of Oklahoma and Arkansas," *Jour. Geol.*, Vol. LIII (1945), pp. 390–97.

[34] "Stratigraphy of the Pennsylvanian Formations of North Central Texas," *Univ. Tex. Bull. 2132* (1922).

extensively on the subsurface Pennsylvanian of the northern Texas area.[35] Both Dr. Plummer and Dr. Cheney are presenting recent findings on the northern Texas area in this symposium. Phillip King[36] and others have worked out the outcropping succession of the Marathon Basin in western Texas; and many areas of subsurface Pennsylvanian, especially in the Permian Basin, are known from oil test records of wells which have extended down to the Ordovician Arbuckle or Ellenburger limestones.

Little is known about the subsurface Pennsylvanian of the Dakotas. The outcropping succession of the Minnelusa in the Black Hills has been described and zoned.[37]

C. C. Branson,[38] A. K. Miller and H. D. Thomas,[39] H. W. Scott,[40] and, recently, the author have been interested in the Amsden, Tensleep, Casper, Quadrant, and other formations in the northern Rockies. Although a few good zone fossils have been found, a large part of the succession consists of barren quartzitic sandstones and nearly barren dense siliceous or dolomitic limestones. The boundaries between the major mid-continent divisions remain to be worked out. Fusulinid evidence shows that there are beds of Morrow, Lampasas, Des Moines, and Missouri age in Wyoming, and there may also be representatives of the Virgil.

In Colorado there are great changes in facies between the thick, clastic, nonmarine Fountain formation of the Denver–Colorado Springs region and the finer-grained and more fossiliferous rocks of the Ingleside, Weber, Hermosa, McCoy, and other named formations in other parts of the state. L. G. Henbest[41] has recently summarized the succession in various parts of Colorado and correlated the zones with those of the mid-continent area. In some parts of the state fusulinids are useful aids in zonation and correlation. The position of the Pennsylvanian-Permian boundary in the thick Maroon formation is not yet determined, since the formation is almost wholly unfossiliferous. Recent work of J. Harlan Johnson,[42] R. Roth,[43] K. G. Brill,[44] and J. W. Vanderwilt[45] is noteworthy.

In New Mexico there are likewise great changes in thickness and facies between comparatively near-by areas. The rocks are, however, somewhat richer in

[35] "Geology of North Central Texas," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIV (1940), pp. 65–118.

[36] "The Geology of the Glass Mountains, Texas. I. Descriptive Geology," *Univ. Tex. Bull. 3038* (1930).

[37] Glenn S. Dillé, "Minnelusa of Black Hills of South Dakota," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XIV (1930), pp. 619–23.

[38] "Pennsylvanian Formations of Central Wyoming," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1199–1226.

[39] "The Casper Formation (Pennsylvanian) of Wyoming and Its Cephalopod Fauna," *Jour. Paleon.*, Vol. X (1936), pp. 715–38.

[40] "Some Carboniferous Stratigraphy in Montana and Northwestern Wyoming," *Jour. Geol.*, Vol. XLIII (1935), pp. 1011–32.

[41] "Stratigraphy of the Pennsylvanian in the West Half of Colorado and in Adjacent Parts of New Mexico and Utah" (abstr.), *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXX (1946), pp. 750–51.

[42] "Paleozoic Formations of the Mosquito Range, Colorado," *U.S. Geol. Surv. Prof. Paper 185B* (1934).

[43] "Type Section of Hermosa Formation, Colorado," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XVIII (1934), pp. 944–47.

[44] "Late Paleozoic Stratigraphy of West-central and Northwestern Colorado," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), pp. 621–56; "Late Paleozoic Stratigraphy of Gore Area, Colorado," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXVI (1942), pp. 1375–97.

[45] "Stratigraphy of Pennsylvanian Hermosa Formation in Elk Mountain, Gunnison County, Colorado," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XIX (1935), pp. 1668–77.

marine faunas than those in other Rocky Mountain areas. The Pennsylvanian has been recently studied by C. E. Needham[46] and zoned on the basis of fusulinids by M. L. Thompson,[47] and the results of correlation studies between several separate depositional basins by C. B. Read and G. H. Wood are presented in another paper in this symposium.

The thick Pennsylvanian successions of Idaho and Utah are imperfectly known. There is said to be at least a 10,000-foot section in the Beaverhead Range on the Idaho-Montana divide which awaits study. The Wells of southeastern Idaho and the Oquirrh of Utah have been studied, respectively, by J. S. Williams[48] and James Gilluly;[49] but both are very thick formations, and much remains unknown about them. The Pennsylvanian of the Uinta Mountains may exhibit lateral-facies gradation between the quartzitic sandstones of western Wyoming and Utah and the arkoses and marine limestones of Colorado, but such transition is inadequately described.

A part of the Supai formation of the Grand Canyon region may be of Pennsylvanian age, but it is largely barren of faunal remains, and the boundary between the Pennsylvanian and the Permian in the Supai has not been located. The Pennsylvanian of southern Arizona seems to be more nearly solid limestone than elsewhere in the United States. These rocks and their faunas await detailed study. In southeastern Utah the thick but local Paradox formation[50] contains the only important evaporites of the Pennsylvanian in the United States. They seem to record barred-basin accumulation.

The Pennsylvanian rocks of (1) Nevada, (2) southwestern California, (3) the Inyo Range of central California, (4) western Oregon, (5) the Blue Mountains of eastern Oregon, and (6) northern and northwestern Washington are poorly known as to age, lithology, succession, and fauna. Many are referred to simply as "Carboniferous" or "late Paleozoic." A small area in central Oregon has recently been carefully studied by C. B. Read and C. W. Merriam[51] and, on the basis of a fossil flora, has been referred to the early Pennsylvanian.

TECHNIQUES APPLIED TO PENNSYLVANIAN STUDIES

Newly advanced techniques applied to Pennsylvanian problems include the isolation of plant microfossils from coals and carbonaceous shales and the zonation of these rocks by a spore-succession column. Researches in this field by R. Kosanke and A. T. Cross are presented as part of this symposium. Other active students using this technique are J. M. Schopf, of the Bureau of Mines, Ray Bentall, and L. R. Wilson.[52]

[46] "Correlation of Pennsylvanian Rocks of New Mexico," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIV (1940), pp. 173–79.

[47] "Pennsylvanian System in New Mexico," *N.M. School of Mines, Bull. 17* (1942).

[48] "Carboniferous Formations in the Northern Blue Springs Hills, near Malad, Idaho," *Proc. Geol. Soc. Amer., 1935* (1936), p. 373.

[49] "Geology and Ore Deposits of the Stockton and Fairfield Quadrangles, Utah," *U.S. Geol. Surv. Prof. Paper 173* (1932), pp. 31–38.

[50] A. A. Baker, C. H. Dane, and J. B. Reeside, "Paradox Formation of Eastern Utah and Western Colorado," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XVII (1933), pp. 963–80.

[51] "A Pennsylvanian Flora from Central Oregon," *Amer. Jour. Sci.*, Vol. CCXXVIII (1940), pp. 107–11.

[52] J. M. Schopf, "Spores from the Herrin (No. 6) Coal Bed in Illinois," *Ill. Geol. Surv., Rept. Investigations No. 50* (1938); J. M. Schopf, L. R. Wilson, and Ray Bentall, "An Annotated Synopsis of Paleozoic Fossil Spores and the Definition of Generic Groups," *Ill. Geol. Surv., Rept. Investigations No. 90* (1944).

Although fusulinids have long been given a prominent place in Pennsylvanian studies because of their widespread distribution, complexity, and value as stratigraphic markers, other groups of microfossils—the ostracodes, conodonts, and smaller foraminifera—have received increasing attention in recent years from C. L. Cooper, who is participating in this symposium, Mrs. Helen Jeanne Plummer,[53] Mrs. Betty Kellett Nadeau,[54] and S. Ellison.[55]

Several groups of larger invertebrates, such as the single corals, trilobites, pelecypods, and Bryozoa, have been subjects of recent investigation by R. M. Jeffords,[56] J. M. Weller,[57] N. D. Newell,[58] R. C. Moore,[59] M. K. Elias,[60] J. B. Knight,[61] C. O. Dunbar and G. E. Condra,[62] and others. Weller summarizes the present and prospective usefulness of invertebrate fossils in interregional correlation and exact zonation of the Pennsylvanian in another paper in this program.

Leaf impressions have been relied upon for years as Pennsylvanian guide fossils, although many of the widespread and important species of plants are still manuscript species, awaiting adequate description and illustration. Charles Read, our principal student of Paleozoic leaf floras, presents the status of Pennsylvanian floras as aids in stratigraphic work in another paper in this symposium.

Electric well logging has permitted a greatly improved tracing of thin subsurface zones in the heterogeneous Pennsylvanian column as compared with the older drillers' logs or even samples furnished by the driller. Drilling-time logs, samples caught by the geologist at the well, and caliper surveys of hole diameter are other useful new tools in the subsurface Pennsylvanian. Radioactive logs have been used little thus far in stratigraphic work; but, because of greater concentration of radioactive materials in organic-rich zones, they may aid in picking out thin coal and carbonaceous shale beds.

Ecologic studies of Pennsylvanian faunas and floras have been made by comparatively few, notably David White,[63] M. K. Elias,[64] and a student now working under L. M. Cline on a statistical study of fossil frequency of vari-

[53] "Smaller Foraminifera in the Marble Falls, Smithwick, and Lower Strawn Strata around the Llano Uplift in Texas," *Univ. Tex. Pub. 4401* (1945), pp. 209–71.

[54] "Ostracodes of the Upper Pennsylvanian and Lower Permian of Kansas," *Jour. Paleon.*, Vol. VII (1933), pp. 69–108; Vol. VIII (1934), pp. 120–38; Vol. IX (1935), pp. 132–66.

[55] "Revision of the Pennsylvanian Conodonts," *Jour. Paleon.*, Vol. XV (1941), pp. 107–43.

[56] "Lophophyllid Corals from Lower Pennsylvanian Rocks of Kansas and Oklahoma," *Kan. Geol. Surv. Bull. 41* (1942), pp. 185–260.

[57] "Carboniferous Trilobite Genera," *Jour. Paleon.*, Vol. X (1936), pp. 704–14; "Evolutionary Tendencies in American Carboniferous Trilobites," *ibid.*, Vol. XI (1937), pp. 337–46.

[58] "Late Paleozoic Pelecypods: Pectinacea," *Kan. Geol. Surv.*, Vol. X (1937); "Late Paleozoic Pelecypods: Mytilacea," *ibid.*, Vol. X, Part II (1942).

[59] "New Crinoids from Upper Pennsylvanian and Lower Permian Rocks of Oklahoma, Kansas, and Nebraska," *Denison Univ. Bull.*, Vol. XXXIV (1939), pp. 171–279, and other crinoid articles.

[60] "Paleozoic Fenestrate Bryozoa," *Jour. Paleon.*, Vol. XI (1937), pp. 316–34.

[61] "The Gastropods of the St. Louis, Missouri, Pennsylvanian Outlier," *Jour. Paleon.*, Vol. IV (1930), suppl.; Vol. V (1931), pp. 1–15, 177–229; Vol. VI (1932), pp. 189–202; Vol. VII (1933), pp. 30–58, 359–92; Vol. VIII (1934), pp. 139–66, 433–47.

[62] "Brachiopoda of the Pennsylvanian System of Nebraska," *Neb. Geol. Surv. Bull. 5* (2d ser., 1932).

[63] "Climatic Implications of the Pennsylvanian Flora," *Ill. Geol. Surv. Bull. 60* (1931), pp. 271–82.

[64] "Depth of Deposition of the Big Blue (Late Paleozoic) Sediments in Kansas," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 403–32.

ous species in the Exline limestone of Iowa. Further studies of this sort will aid in understanding the significance of changes in lithology, both vertically and laterally, which affect the Pennsylvanian in nearly all areas of its outcrop.

Few studies have been made of insoluble residues of Pennsylvanian limestones, and these suggest that the technique, while useful, is somewhat less valuable than it has proved to be with the Cambro-Ordovician limestones and dolomites through studies by McQueen and others. Few mineralogical studies of Pennsylvanian sandstones have been made. Those few with whose results the author is familiar, principally in the Middle West, suggest that most of the particles are stable mineral species released from an older sediment and redeposited in the Pennsylvanian. Perhaps in the Rocky Mountains, where crystalline source rocks were closer at hand, such studies would throw more light on the provenance of the minerals. It is hoped that researches related to the exchangeable bases associated with clay minerals may aid in determining whether a particular clay or shale was deposited in fresh or marine waters.

Most paleogeographic maps have generalized the geography of a portion of the Pennsylvanian, not indicating that during such an interval of time the sea may have advanced eastward from Kansas to Illinois or Pennsylvania several times, with an equal number of periods of emergence. The accomplishment of more exact correlations, such as those of Cline and his associates, through the detailed tracing of beds from Kansas across Missouri and Iowa to Illinois should permit mapping the geography of a particular brief stage of one of the Pennsylvanian epochs to a degree heretofore never undertaken.

SUMMARY OF CLASSIFICATION OF THE PENNSYLVANIAN FORMATIONS OF TEXAS, WITH SPECIAL REFERENCE TO THE LOWER PENNSYLVANIAN OF THE LLANO REGION

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ABSTRACT

Middle and Upper Pennsylvanian beds of Texas are well known and are subdivided into a series of formations on the basis of lithology and fossils. The Lower Pennsylvanian, however, which outcrops in central Texas is more complex. Recent field work has distinguished three formations, one of which is subdivided into four members. These are briefly described and lists of characteristic fossils are presented.

GENERAL DESCRIPTION

The Pennsylvanian sediments of north-central Texas have a maximum thickness of about 5,400 feet. The lower 400–600 feet of this section consist of limestone; and the next 1,000–3,600 feet, of predominantly clastic sediments, are made up of siliceous and calcareous shales, thick sandstones, and a few limestones. The upper 1,600 feet consist of alternating limestones and calcareous shales, with a few coal seams, sandstone, and conglomerate layers. With the exception of groups of strata in the upper series, the Pennsylvanian formations in Texas do not show anything like complete cycles of sedimentation like those seen in the geologic section of Illinois, Kansas, and northern Oklahoma. The division of the strata into series, groups, and formations is made on a basis of lithology and paleontology. This system of classification, as far as the Upper Pennsylvanian strata go, is now quite satisfactorily established, and, except for minor details, Texas geologists are agreed fairly well on the nomenclature and correlations. On the other hand, the Lower Pennsylvanian formations, until recently, have been less well known paleontologically, and their divisions, classification, and correlation have been the subject of much discussion ever since the first work by Hill, Dumble, Cummins, and Sidney Paige.

CLASSIFICATION

The general classification of the strata in the middle and upper portions of the Pennsylvanian section in central Texas is shown in Table 1, to which has been added a list of the more common index fossils that characterize the various divisions.

The upper formations are classified into three groups: Strawn of Des Moines age, Canyon of Missouri age, and Cisco of Virgil age. These series are subdivided into convenient mappable units with a persistent, easily recognizable limestone at the top and, in most cases, a coarse sandstone or basal conglomerate at the base. In several cases an easily recognizable unconformity, with definite interformational channeling, separates the formations distinctly. The limestones have been mapped in great detail by oil geologists of at least three decades. In most cases they stand out clearly on aerial photographs and therefore form the most convenient basis for differentiation. On the other hand, with the exception of some interesting work by Wallace Lee, the intervening shales, sandstone,

and coals have been very largely neglected and deserve much more attention. A detailed study of northern Texas clastic sediments is a rich field for future research. Many geologists have asked why we do not drop the local Texas names—Strawn, Canyon, and Cisco—and adopt the wider-ranging mid-continent nomenclature, Des Moines, Missouri, and Virgil. This procedure in many cases can be adopted advantageously. On the other hand, because of the Arbuckle Mountains, the Cretaceous overlap, and change in facies along the Red River, it is not possible to trace any group of beds through from one area of deposition into another. Further, a very detailed study of fossil zones indicates that in many cases the successions of sediments in widely separated areas are not exactly equivalent—hiatuses occur in one area, expansion of sedimentation in another, transgressions of sediments in a third, etc. The use of a local name ties the particular formation or group under discussion to a given sedimentary area and indicates at once its geographical environment. This, in some

TABLE 1

CLASSIFICATION OF PENNSYLVANIAN FORMATIONS IN CENTRAL TEXAS

SERIES		DEFINITION IN TEXAS	FUSULINID ZONES	CHONETID ZONES	AMMONOID ZONES
Texas	Mid-Continent				
Cisco.....	Virgil	Base of Cisco Lake ss. outcropping at Cisco L. spillway to top of Home Cr. lst. Includes lower Harpersville Fm. and the Thrifty and Graham Fms.	*Triticites ventricosa* (large robust forms) *Dunbarinella plummeri*	*Chonetes transversalis* *C. alata* *Lissochonetes plattsmouthensis*	*Uddenites serratus* *U. schucherti* *Shumardites simondsi*
Canyon...	Missouri	Top of Home Cr. lst. to base of L. Pinto ss. in north Texas and to base of Rochelle cgl. in central Texas. Includes Caddo Cr., Brad, Graford, and Lone Camp Fms.	*Triticites* (small forms) *T. ohioensis* *T. irregularis*	*Chonetina primitiva* *C. wyandottensis* *C. verneuilana*	*Shumardites cuyleri* *S. fornicatus* *Paraschistoceras reticulatum*
Strawn...	Des Moines	Base of Lake Pinto ss. or base of Rochelle cgl. to top Smithwick shale. Includes Mineral Wells (restricted), Garner, and Millsap Lake Fms.	*Fusulinella* (advanced type) *Fusulina* *Wedekindellina*	*Mesolobus euampyzus* *M. rochellensis* *M. mesolobus*	*Wellerites mohri* *Pintoceras postvenatum*
Bend.....	Atoka	Top of Smithwick shale to base of Big Saline lst. Includes Smithwick and Big Saline Fms.	*Fusulinella* (restricted type) *Profusulinella* *Pseudostaffella*	*Chonetes dominus* (large) *Paeckelmannia derelicta*	*Gastrioceras smithwickense* *G. occidentale* *Branneroceras branneri* *Phaneroceras compressum*
Sloan.....	Morrow	Base of Big Saline Fm. to top of Barnett shale or to top of Chappel or Ellenburger, where Barnett is absent. Includes Sloan Fm.	No fusulinids as yet observed in Texas	*Chonetes choteauensis*	*Phaneroceras nolinense*

cases, is a distinct advantage. On the other hand, system names and series names should be interstate and international to indicate long-distance correlations.

The Lower Pennsylvanian strata occur around the Llano region in central Texas (Fig. 1). These strata present more difficulties in classification than the upper ones do. Many attempts have been made, and many more will be made. The author's latest contribution is shown in Table 2. This differentiation of these strata into formations, like that of the upper portion of the Pennsylvanian section, is based on lithology and paleontology (Fig. 2).

DESCRIPTION OF UNITS

Sloan formation.—The Sloan formation is thin-bedded, cryptocrystalline, dense, black limestone. The fossils are numerous and fairly well preserved. The more typical forms are listed below:

LIST OF FOSSILS COLLECTED FROM THE SLOAN FORMATION

ANTHOZOA

Stereocorypha annectans Moore and Jeffords
Lophophyllidium adaptertum Moore and Jeffords
Barytichisma crassum Moore and Jeffords
B. callosum Moore and Jeffords
B. repletum Moore and Jeffords
Cladochonus fragilis Mather
Amplexocarinia corrugata (Mather)

CRINOIDEA

Ethelocrinus texasensis Moore and Plummer
Cibolocrinus punctatus Moore and Plummer
Diphuicrinus croneisi Moore and Plummer

BRACHIOPODA

Chonetes choteauensis Mather
Juresania wilberana (McChesney)
Paeckelmannia sp.
Horridonia globosa (Mather)
Marginifera roemeri Girty
Linoproductus nodosus (Newberry)
Dictyoclostus morrowensis (Mather)
Rhynchopora illinoisensis (Worthen)
R. magnicosta Mather
Spirifer opimus Hall
Punctospirifer campestris (White)
P. transversus (McChesney)
Composita ozarkana Mather
C. deflecta Mather
C. elongata Dunbar and Condra
Cleiothyridina orbicularis (McChesney)
Squamularia? perplexa (McChesney)
Hustedia miseri Mather

PELECYPODA

Edmondia, n.sp.
Myalina wyomingensis (Lea)
M. congeneris Walcott
Leda sp.
Parallelodon obsoletus Meek
Posidonia sp.
Pterinopectinella, n.sp.
Aviculopecten halensis Mather
Lithophaga sp.
Pleurophorus occidentalis Meek and Hayden
Allorisma reflexum Meek

GASTROPODA

Worthenia tabulata (Conrad)
Trepospira sp. indet.
Colpites cf. *C. minutus* (Sayre)
Naticopsis aff. *N. subnovata* Worthen
Orthonychia, n.sp.
Meekospira peracuta (Meek and Worthen)
Pharkidonotus, n.sp.

AMMONOIDEA

Phaneroceras nolinense (Cox)

On this list about 60 per cent of the species appear to have fairly close affinities with the Morrow of Arkansas. The other 40 per cent of the species appear to be slightly younger than the Morrow. The most characteristic fossils which are common and easily recognized are *Dictyoclostus morrowensis*, *Marginifera roemeri*, *Linoproductus nodosus*, and *Phaneroceras nolinense*. The Sloan may be recognized by this assemblage anywhere.

Big Saline formation.—The Big Saline formation is almost wholly limestone. It consists of six members—four east of

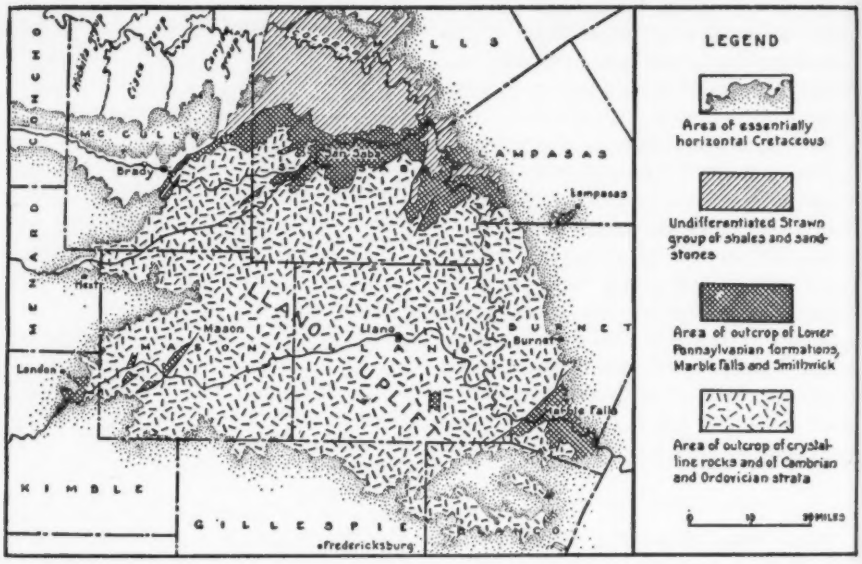

FIG. 1.—Map of the area around the Llano Uplift, showing the regional distribution and relationships of the older Paleozoics, the Lower Pennsylvanian, the Strawn group, Canyon group, and Cisco group of the Middle and Upper Pennsylvanian and the essentially horizontal Lower Cretaceous blanket that once covered the entire area but has been partially removed by the Colorado River and its tributaries. (Details of the Lower Pennsylvanian geology by F. B. Plummer; border of Lower Cretaceous in Gillespie County by V. E. Barnes; rest of map compiled from several published sources.)

TABLE 2

GROUP	FORMATION	MEMBER	
		East of Cavern Ridge	West of Cavern Ridge
	Smithwick	Siltstone facies Shale facies	Absent .....
Bend (Atoka).....	Big Saline	Brister Lemons Bluff Aylor Gibbons	Soldiers Lemons* Bluff Brook Ranch Gibbons
Morrow (Upper Morrow).....	Sloan	Present	Absent

* Absent southwest of Brook Ranch in McCulloch County.

Cavern Ridge and two additional members west of the ridge, as shown in Table 2. A marked unconformity separates the Sloan formation from the Big Saline, and in many places the entire thickness of the Sloan was removed by erosion before the Big Saline strata were deposited. In the eastern area there is the Brister or massive limestone at the top, the Lemons Bluff sponge-spicule beds in the middle, the Aylor oölite below, and the Gibbons conglomerate at the base.

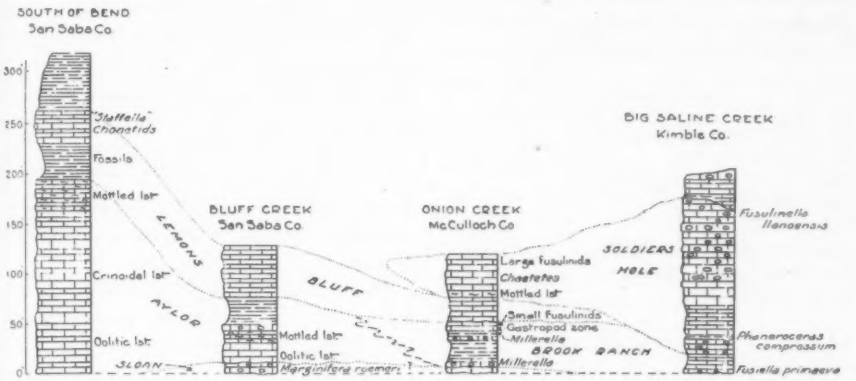

FIG. 2.—Stratigraphic sections, showing correlation of Pennsylvanian formations and members in the Llano region.

Gibbons conglomerate.—The lower or Gibbons conglomerate consists of a layer of chert and limestone pebbles, averaging $\frac{1}{2}$ inch in diameter and 1 inch–3 feet thick, though commonly only about 6 inches thick. The layer is absent in many places, and in some cases the line of demarcation between the Big Saline and the Sloan is difficult to determine.

Aylor member.—The Aylor member has a bed of oölite 2–10 feet thick, which thickens toward the east and on the Colorado River has a total thickness of 100 feet, overlain by light-colored, coarsely crystalline, chert-bearing, massive, somewhat oölitic limestone. The fossils are not plentiful and have not been studied in detail.

Lemons Bluff member.—The Lemons Bluff member of the Big Saline is quite distinctive. It is 20–60 feet thick and is made up of about 50 per cent sponge spicules and 50 per cent dense subcrystalline limestone. It occurs in bed 2–12 inches thick, separated by thin shale partings, so that the face of a cliff of this member looks like a masonry wall. It has been traced from Lampasas on the east to Brady on the west, as shown in Figure 2, and its distinctive and easily recognizable characteristics make it of much aid in working out Lower Pennsylvanian stratigraphy. It may be identified easily by its spicules, which show up in thin sections and in insoluble residues, and by the fact that the high-silica content allows the rock to melt below 2000° F. The other Lower Pennsylvanian limestones do not melt but, upon heating, change to calcium oxide, with loss of carbon dioxide. The Lemons Bluff member of the Big Saline is quite fossiliferous. The following fossils have been identified:

MOST COMMON SPECIES FROM THE LEMONS BLUFF

FORAMINIFERA

Cribrostomum marblense H. J. Plummer
Staffella? sp.
Millerella marblensis Thompson

ANTHOZOA

Empodesma imulum Moore and Jeffords
Lophophyllidium extumidum Moore and Jeffords
L. idonium Moore and Jeffords
Paracaninia? sana Moore and Jeffords
Michelinia referta Moore and Jeffords
Striatopora religiosa Moore and Jeffords
Cladochonus texasensis Moore and Jeffords
Chaetetes favosus Moore and Jeffords

BRACHIOPODA

Neospirifer goreii (Mather)
Spirifer opimum Hall
Rhipodomella pecosi (Marcou)
Chonetes dominus King
Chonetina sp.
Paeckelmannia derelicta King
Horridonia bullata (Mather)
H. globosa (Mather)

GASTROPODA

Pharkidonotus bendensis, n.sp.
Straparolus savagei Knight

AMMONOIDEA

Phaneroceras compressum (Hyatt)
Paralegoceras texanum (Shumard)
Brannerоceras branneri (Smith)

ORTHOCERATOIDEA

Rayonnoceras croneisi, n.sp. (MS.)

NAUTILOIDEA

Ephippioceras divisum Hyatt
Coloceras sp.
Metacoceras sp.
Endolobus gibbosus Hyatt
Titanoceras sp.
T. illinoisensis (McChesney)
Solenochilus branneri Miller, Dunbar, and Condra

The most characteristic of these are *Neospirifer goreii*, *Spirifer opimus*, *Chonetes dominus*, and *Paralegoceras texanum*.

Brister member.—The Brister, or upper, member consists of medium-thick beds of light-colored, coarsely crystalline limestone containing fossils quite similar to those in the Lemons Bluff member below, but generally richer in corals, especially *Chaetetes*, crinoids, and Bryozoa.

West of Cavern Ridge the strata are somewhat different in appearance and contain a different fauna, and therefore two of the members have been given different names from those on the east side. The Gibbons conglomerate consists of limestone pebbles, nodules, and waterworn fossils with almost no chert. The Lemons Bluff member thins out south of Brady, and the Soldiers Hole beds above rest directly on the Brook Ranch beds below.

Brook Ranch member.—The Brook Ranch beds are black, hard, subcrystalline, light-colored, cherty limestones and contain fossils quite different from those found in the Aylor member east of the ridge. Here are the primitive fusulinids, *Fusiella primaeva*, an interesting group of gastropods recently studied by Brookes Knight, and an entire absence of the oölitic deposits found in the Aylor. None of us has yet been able to correlate any of these Brook Ranch beds with strata east of Cavern Ridge.

Soldiers Hole member.—The upper, or Soldiers Hole, member is best developed southwest of Brady and along Big Saline Creek southeast of London. It consists of moderately massive, coarsely crystalline, light-colored limestone, in beds 2–12 feet thick, separated by distinct bedding planes. The most common fossils are as follows:

LIST OF FOSSILS FROM THE SOLDIERS HOLE MEMBER OF THE BIG SALINE FORMATION

FORAMINIFERA

Fusulinella llanoensis (Thomas)
Cribrostomum marblense H. J. Plummer
Endothyranella armstrongi sobrina H. J. Plummer
Endothyra distensa H. J. Plummer
Polytaxis scutella (Cushman and Waters)
Bradyina sp.

ANTHOZOA

Lophophyllidium extumidum Moore and Jeffords
Amplexocarinia corrugata (Mather)
Pseudozaphrentoides lepidus Moore and Jeffords
P. spatiosus Moore and Jeffords
Rodophyllum texanum Moore and Jeffords
Neokoninckophyllum simplex Moore and Jeffords
N. gracile Moore and Jeffords
Michelinia latebrosa Moore and Jeffords
Chaetetes eximius Moore and Jeffords
C. subtilis Moore and Jeffords
C. favosus Moore and Jeffords

BRACHIOPODA

Orthotetes robusta (Hall)
O. kaskaskiensis (McChesney)
Chonetes dominus King
Horridonia globosa (Mather)
Marginifera gallatinensis (Girty)
M. welleri Mather
M. haydenensis Girty
Linoproductus sp.
L. platyumbonus Dunbar and Condra
Dictyoclostus sp.?
Spirifer matheri Dunbar and Condra
S. opimus Hall
S. rockymontanus Marcou
Neospirifer cameratus (Morton)
N. goreii (Mather)
Punctospirifer transversus (McChesney)
Composita ozarkana Mather
C. elongata Dunbar and Condra
C. trilobata Dunbar and Condra
C. gibbosa Mather
C. wasatchensis Mather
Cleiothyridina orbicularis (McChesney)
Schizophoria resupinoides (Cox)
Roemerella sp.

PELECYPODA

Allorisma costatum Meek and Worthen
A. terminale Hall
Solenomya subradiata Herrick

GASTROPODA

Euphemites sp. indet.
Orthonychia, n.sp.
Mourlonia, n.sp.
Pharkidonotus, n.sp.

AMMONOIDEA

Pronorites llanoensis Plummer and Scott

The fossils indicate that the beds are younger than the Lemons Bluff strata, and they may prove to be equivalent to, or perhaps even younger than, the Smithwick. The most characteristic species are *Fusulinella llanoensis*, *Neospirifer cameratus*, *N. goreii*, *Dictyoclostus inflatus*, and *Pronorites llanoensis*.

Smithwick formation.—The Smithwick formation is black, fissile, highly siliceous shale, containing, in its upper portion, layers and lentils of fine, hard, firmly cemented siltstone. It is thickest in syncline areas and thins by loss of lower beds as it passes over anticlines, where its base, in some cases, is marked by a thin pebble conglomerate. Therefore, it appears that some deformation took place in central Texas at the end of the Big Saline epoch and that the Smithwick sediments filled the depressions and overlapped onto the elevations. There is a rather rich fauna in the basal Smithwick beds. The upper Smithwick in most places is unfossiliferous. The following list has been identified:

LIST OF FOSSILS COLLECTED FROM THE SMITHWICK FORMATION

ANTHOZOA

Hapsiphyllum tumidum Moore and Jeffords
H. retusum Moore and Jeffords
Zaphrentoides eccentricus Moore and Jeffords
Cummingsia aplata (Cummins)

Michelinia referta Moore and Jeffords
Palaeacis testata Moore and Jeffords
Zaphrentis sp.
Neokoninckophyllum arcuatum Moore and Jeffords

BRYOZOA

Fenestella cf. *F. regalis* Ulrich

BRACHIOPODA

Orbiculoidea missouriensis (Shumard)
Paeckelmannia derelicta King
Linoproductus sp.
Marginifera muricatina Dunbar and Condra
Dictyoclostus portlockianus (Norwood and Pratten)
Wellerella osagensis var. *immatura* Dunbar and Condra
Crurithyris planoconvexa (Shumard)
Cleiothyridina sp.
C. sublamellosa (Hall)
Hustedia brentwoodensis Mather
Juresania nebrascensis (Owen)

PELECYPODA

Solenomya sp.
Edmondia ovata (Meek and Worthen)
E. glabra Meek
Nucula, n.sp.
N. summa, n.sp.
Nuculopsis ventricosa (Hall)
Nuculana bellistriata (Stevens)
N. plicata, n.sp.
Nu. arata (Girty)
Conocardium snideri Morgan
Allorisma sp.

GASTROPODA

Pharkidonotus, n.sp.
Euphemites, n.sp.
Neilsonia, n. sp.
Glabrocingulum, n.sp.
Trepospira, n.sp.
Goniospira sp.
New g. and n.sp.
Straparolus savagei Knight
Amphiscapha subquadrata (Meek and Worthen)
Straparolus, n. sp.
Soleniscus (*Macrocheilina*) *ventricosus* (Hall)
New g. and n. sp.

CEPHALOPODA—PSEUDORTHOCERATIDEA

Orthoceras wapanuckense Girty
Pseudorthoceras knoxense (McChesney)
Mooreoceras normale Miller, Dunbar, and Condra
Bactrites postremus Miller
Dolorthoceras, n. spp.
Rayonnoceras hueconense Miller, Dunbar, and Condra

CEPHALOPODA—NAUTALOIDEA

Brachycycloceras normale Miller, Dunbar, and Condra
Coloceras sp.
Liroceras liratum (Girty)
Temnocheilus sp.
Metacoceras sp.
Solenochilus sp.

CEPHALOPODA—AMMONOIDEA

Pronorites sp.
P. arkansasensis Smith
Daraelites (*Boesites*) *scotti* Miller and Furnish
Nuculoceras smithwickense Plummer and Scott
Phaneroceras compressum (Hyatt)
Paralegoceras sp.
P. shumardi Plummer and Scott
Glaphyrites hyattianus (Girty)
G. angulatus (Girty)
G. raymondi Plummer and Scott
Goniolobоceras sp.
Gastrioceras occidentale (Miller and Faber)
G. smithwickense Plummer and Scott

The most characteristic fossils of the Smithwick are *Gastrioceras occidentale*, *G. smithwickense*, *Daraelites* (*Boesites*) *scotti*, *Cumminsia aplata*, and *Straparolus savagei*. None of these except the last one occurs in the Big Saline below.

Strawn-Smithwick contact.—Another deformational unconformity occurs at the top of the Smithwick. The Strawn strata were deposited on the deformed and somewhat eroded Smithwick beds. The unconformity evidently represents a long hiatus because not only is the Smithwick fauna in every way unlike the Strawn fauna, but much compaction settling and widespread deformation took place before the Strawn strata were deposited. In many places the deformation was such that the Smithwick and Marble Falls strata dip east while the Strawn beds are inclined to the west. In

fact, the unconformity between the Bend and the Strawn is the most pronounced in a section replete with unconformities.

SUMMARY

It will be apparent from these brief descriptions that the Lower Pennsylvanian strata of central Texas, long divided into only two formations—the Marble Falls limestone below and the Smithwick shale above—are now divisible into three formations—Sloan, Big Saline, and Smithwick—recognizable on a basis of lithology and paleontology. The Big Saline formation, by its fossils, pebble conglomerate, and sponge-spicule content, is easily separated into four members on each side of the Cavern Ridge barrier. Furthermore, the beds on the west side of the ridge are apparently somewhat younger than stratigraphically equivalent strata on the west, indicating that the Big Saline sea in central Texas transgressed from the east toward the west, so that slightly younger and more advanced types of organisms differentiate the beds in the two regions. For this reason two of the members—the Soldiers Hole and the Brook Ranch—on the west side of the ridge are given different names from beds of equivalent stratigraphic position on the east side. The diagram (Fig. 2) illustrating typical geologic sections from east to west across the Llano region will perhaps make these relationships somewhat clearer.

PENNSYLVANIAN CLASSIFICATION AND CORRELATION PROBLEMS IN NORTH-CENTRAL TEXAS

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ABSTRACT

This paper is intended as a commentary on past and present classifications and correlations of the Pennsylvanian rocks of north-central Texas, with suggestions regarding solution of some of the regional problems involved. It is apparent that the problems are too complex and numerous to expect early settlement. The following major premises and conclusions are presented:

1. The Pennsylvanian rocks of north-central Texas may now be correlated with considerable certainty with those of other regions.

2. A time-stratigraphic classification in agreement with a standard time-stratigraphic classification for the system would have important advantages.

3. The principal standard section of reference should be established in the northern Appalachian region, with time-stratigraphic divisions based, in part, on data available from other regions, particularly the Mid-Continent.

4. The standard and regional time-stratigraphic divisions should be based on broad studies of structural and lithologic data, as well as on presently available paleontological evidence, in the hope of establishing widely recognizable, distinctive, and equivalent time-stratigraphic divisions which would require a minimum revision of boundaries heretofore used in the various major Pennsylvanian provinces.

5. Division of the Pennsylvanian system into six series appears appropriate, the major Pottsville and Pittsburgh divisions of the northern Appalachian region each being divided into three series, known, respectively, in north-central Texas as the Springer, Morrow, and Lampasas and the Strawn, Canyon, and Cisco.

6. The highest position used for the boundary between these lower and upper major divisions in Pennsylvania appears to agree closely with the usage of the last three decades in north-central Texas, where the boundary between the "subsurface Bend" and the Strawn has been placed above the "Caddo" limestone of oil-field terminology.

7. The top of the Caddo limestone occurs at a variable position in this region. The upper boundary of the youngest Caddo limestone has been used herein as a boundary between the Lampasas and the Strawn series. It is thought to be approximately equivalent to the Dornick Hills–Deese boundary of the Ardmore basin, the Boggy-Thurman boundary of eastern Oklahoma, the Tradewater-Carbondale boundary of the *Illinois Geological Survey Bull. 67* (1942), the long-established Kanawha-Allegheny boundary of West Virginia, and the boundary recommended in Pennsylvania on the basis of recent studies. A somewhat lower boundary may ultimately prove more useful.

INTRODUCTION

Extensive drilling for petroleum in north-central Texas has revealed that the Pennsylvanian rocks of this region have a composite thickness of about 10,000 feet as measured in wells from the Fort Worth Basin westward. This is 5,000 feet greater than the maximum composite outcrop section and nearly 9,000 feet thicker than the Pennsylvanian section beneath Permian rocks on the buried major arches in the north and southwest parts of this region, namely, the Muenster and Electra arches of the Red River Uplift and the Concho arch, which extends north-northwest from the present Llano Uplift. Obviously, many problems confront the effort to classify and correlate such a great volume of sedimentary rocks. Complications arise not only from the numerous lithologic, structural, and biotic variables but from the extensiveness of the region and the inadequacy of data in areas of limited drilling or where the Pennsylvanian rocks are covered by the Comanche overlap. Much additional geological information is, of course, expected from future drilling, stimulated by past oil discoveries which total no less than 2,000,000,000 barrels in this region.

Aided in large part by fusulinid

studies, correlations from surface to subsurface are becoming more firmly established in north-central Texas. Transition from classification by local lithologic groups to time-stratigraphic series is progressing, although along somewhat divergent lines, according to the varying degree of emphasis given to (1) paleontologic, structural, and stratigraphic criteria; (2) surface versus subsurface usage; and (3) the classification to which the individual geologist is accustomed, chiefly north-central Texas versus northern Mid-Continent usage.

PROBLEMS OF CLASSIFICATION

GROUPS VERSUS TIME-STRATIGRAPHIC SERIES

Initial studies of Pennsylvanian outcrops in the Brazos and Colorado River valleys of Texas by Cummins, Tarr, Drake, and others a half-century ago gave excellent descriptions of the rock sequences and logical designation of certain divisions or lithologic groups, based largely on similarity of rock characteristics. Similar work progressing in other states resulted in the development of many local classifications, each with names locally derived. The expansion of geological studies has been hampered by the resultant dissimilarity of division boundaries and diversity of names.

The need of time-stratigraphic divisions has become increasingly evident. Knowledge of time relationships of the principal geological features within each basin and the interrelationships between the several major basins has both scientific and economic value. Stratigraphical, structural, and paleontological studies of Pennsylvanian rocks are of special interest because of the enormous energy resources found therein. The 1927 and 1935 Heerlen conferences on the Carboniferous reflect the well-recognized international importance of that part of the geologic column which is commonly called the "Pennsylvanian" and "Mississippian" systems in the United States.

During Pennsylvanian time, downward crustal movements in the Appalachian, southern Mid-Continent, and Marathon regions permitted deposition of clastic shallow-water sediments, several miles thick. By the close of Pennsylvanian time these southwest-trending troughs had become belts of extreme folding, uplift, and thrust faulting. The main axes of crustal adjustments migrated frontally to some extent during successive stages of subsidence, folding, thrusting, elevation, and erosion. To the northwest of these belts of extreme crustal adjustments there developed a number of broad domes, arches, flexures, and intervening basins, more or less transverse but doubtless influenced in large degree by forces and events in the more dominant belt of geosynclines and mountain-building. Extensive foreland areas remained near sea level, as revealed by innumerable alternations from marine to nonmarine deposits. The resulting great lateral changes in the thickness and character of the sediments and in the ecological conditions and subsequent succession of structural modifications have all contributed to the complex whole and have multiplied the difficulties of correlations and of establishment across the continent of equivalent time-stratigraphic divisions of this great rock system.

APPALACHIAN AND MID-CONTINENT STANDARD SECTIONS

Data from the various Pennsylvanian provinces in North America give increasing support to the view that, within these several related troughs, basins, and foreland areas, major changes took place

with sufficient contemporaneity that significant partition of Pennsylvanian time into several major epochs can be made with considerable reliance. That certain coal and marine limestones can be traced for hundreds of miles has been pointed out by many writers. The observed cyclic deposition and marked floral changes imply important fluctuations of sea level and climatic changes, which would leave very widespread, nearly simultaneous, records in the swamp, playa, and shallow marine deposits of the Pennsylvanian system. It therefore appears both desirable and feasible to work toward the establishment of equivalent time-stratigraphic divisions of this system in the various Pennsylvanian provinces. A major step in this direction was the publication in 1944 of the report on correlation of Pennsylvanian formations of North America by a National Research Council subcommittee, R. C. Moore, chairman.[1] Many specialists in Pennsylvanian stratigraphy from various parts of the United States aided in the preparation of this correlation chart, with its five major time-stratigraphic divisions and its more than sixty regional sections. A subsequent report[2] by a subcommittee of the Geologic Names and Correlation Committee of the American Association of Petroleum Geologists advocated world-wide recognition of the Pennsylvanian rocks as a system rather than as a series or subsystem and the establishment in North America of costandard Appalachian and Mid-Continent standard sections having six main time-stratigraphic divisions. In the latter report the Lower Pennsylvanian was divided into two series, instead of one as in the National Research Council subcommittee report. A forthcoming paper will review certain evidence supporting division of the Lower Pennsylvanian of the Mid-Continent region into two series (Springer and Morrow). More than one hundred and twenty-five species of invertebrate fossils have now been collected and identified from the 4,000 feet of Springer rocks in the Ardmore Basin by G. E. Condra and M. K. Elias. The assemblage is clearly intermediate between Chester and Morrow faunas, according to these investigators.[3]

Classification by standard time-stratigraphic divisions, differentiated by major biotic, structural, and depositional changes, should eventually bring much greater stability and usefulness to the various provincial stratigraphic classifications than would be attainable otherwise.

PRINCIPAL PENNSYLVANIAN STANDARD REFERENCE SECTION

Use of the Appalachian and Mid-Continent sections of the Pennsylvanian system as costandards gives recognition to the equal, or nearly equal, importance, as well as to the complementary nature, of these two sections for purposes of Pennsylvanian classification. Some geologists have advocated that the Mid-Continent Pennsylvanian should be used as the principal standard because of better development in the upper part of the system, excellent outcrops, central location, greater marine content, more diverse structural history, and greater progress in classification of these rocks into time-stratigraphic divisions. Others

[1] R. C. Moore *et al.*, "Correlation of Pennsylvanian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), pp. 657–706.

[2] M. G. Cheney *et al.*, "Classification of Mississippian and Pennsylvanian Rocks of North America," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIX (1945), pp. 125–69.

[3] Personal communications, March and December, 1946.

maintain that the principal standard section should be in Pennsylvania and vicinity, where the type section of the system is located and where differentiation into series first began, the name "Allegheny series" having been proposed by Rogers in 1840.

Plant fossils are more abundant and better known in the Appalachian region than in the Mid-Continent. Doubtless, useful nonmarine faunas are also present as in the western European Coal Measures.[4] Several marine invasions extended into the Appalachian region during Upper Pottsville and subsequent Pennsylvanian time, leaving representative fusulinid, brachiopod, and other faunas. Because coal deposits are of such great economic importance and are particularly characteristic of the Pennsylvanian system, it seems appropriate that the type and principal standard section should be in an area having numerous and widespread coal beds and abundant, well-preserved coal-forming floras, as is especially true of the Appalachian region.

Most geologists in the United States prefer to use the name "Pennsylvanian system" rather than "Upper Carboniferous series." This implies the use of the northern Appalachian section as a world type and standard for this system. The Appalachian section is both closer and more similar to the western European Upper Carboniferous or Coal Measures than is the Mid-Continent section; therefore, it is probably more useful for correlation of the North American and European sections.

Contrary to earlier impressions, accumulating data now indicate that the flora and fauna are in virtual agreement in the correlation of much of the Appalachian, Illinois, and Mid-Continent sections. The paleontological data and relationships have been discussed at some length in the two subcommittee reports previously mentioned. Present regional and interregional co-ordination awaits as much or more upon solution of problems of classification as of correlation. The choice of a principal section of reference and its organization into major time-stratigraphic divisions appears essential to the development of a more complete understanding of Pennsylvanian rocks of North America and of any portion thereof.

A questionnaire sent to 28 state geological surveys in 1941, requesting a statement of preference as to the most desirable standard section of reference for the Pennsylvanian system brought 22 replies; 15 favored the Pennsylvania, West Virginia, Ohio region, 5 the Mid-Continent, and 1 each West Texas and New Mexico.

NAMES OF STANDARD MID-CONTINENT SERIES

The foregoing considerations encourage efforts to classify the Pennsylvanian rocks of north-central Texas and elsewhere into time-stratigraphic or series divisions to replace earlier rock groups. The rules of nomenclature provide for revision of boundaries and change of rank of a stratigraphic sequence without change of name. Well-established provincial names are not readily displaced, and, furthermore, they have both geographical and more or less definite time significance. An attempt to revise the north-central Texas Pennsylvanian into divisions having series rank was made in 1939 as part of a symposium on the geology of West Texas.[5] The changes then

[4] A. E. Trueman, "Stratigraphical Problems in the Coal Measures of Europe and North America," *Quart. Jour. Geol. Soc. London*, Vol. CII (1946), pp. xlix–xcii and Pl. A.

[5] M. G. Cheney, "Geology of North-central Texas," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIV (1940), Fig. 9 and p. 109.

proposed have found acceptance in part, but no concordance of usage has as yet become established. Some geologists coming to Texas from the northern Mid-Continent region have advocated the replacement of Texas names by those of the related, though separate, province north of the Arbuckle Mountains. Such a proposal was made in 1946 in a stimulating paper by R. C. Spivey and T. G. Roberts.[6] Texas geologists, interviewed in 1939 on this question, expressed an overwhelming preference for the adoption of well-known Texas names for series to be set up in north-central Texas, such series to have boundaries equivalent to those established or appropriate for the northern Mid-Continent region.

Use of the Springer, Morrow, Lampasas, Des Moines, Missouri, and Virgil as the standard Mid-Continent series sequence appears to be proper, based on the rule of priority. It may prove desirable to use each of these names only in the particular province of its origin. Elsewhere correlative divisions may bear appropriate provincial series names and be referred to as of Springeran, Morrowan, Lampasan, Desmoinesian, Missourian, or Virgilian age to show time relationships. Suffixes have been used sparingly in this paper, although, admittedly, exactness of meaning and greater consistency are achieved by the use of suffixes such as *-ian*, *-an*, *-ous*, *-ic*, or *-ene* to indicate time and time-stratigraphic significance. On the other hand, designation of rank, whether series, group, or formation, shows the meaning intended. Brevity and euphony are more commonly retained and redundancy avoided when the suffix is omitted. Opposing views on this subject have been ably reviewed by C. W. Tomlinson.[7]

[6] "Lower Pennsylvanian Terminology in Central Texas," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXX (1946), pp. 181–86.

NORTH-CENTRAL TEXAS STRATIGRAPHY

The Pennsylvanian of north-central Texas presents numerous difficulties of classification and correlation, chiefly because of incomplete paleontological data, lack of index fossils in parts of the section, changing facies, wide separation between some outcrop areas, and great differences between basin and uplift sections.

Chart I shows the classification and terminology of this and certain earlier papers, particularly *University of Texas Bulletin 3232*.[8] Areas where five of the six Pennsylvanian series crop out in north-central Texas are shown in Figure 1. The Springer series is represented in wells in the northeast part of this region but has not been recognized at the surface.

NEW NAMES AND NEW USAGE

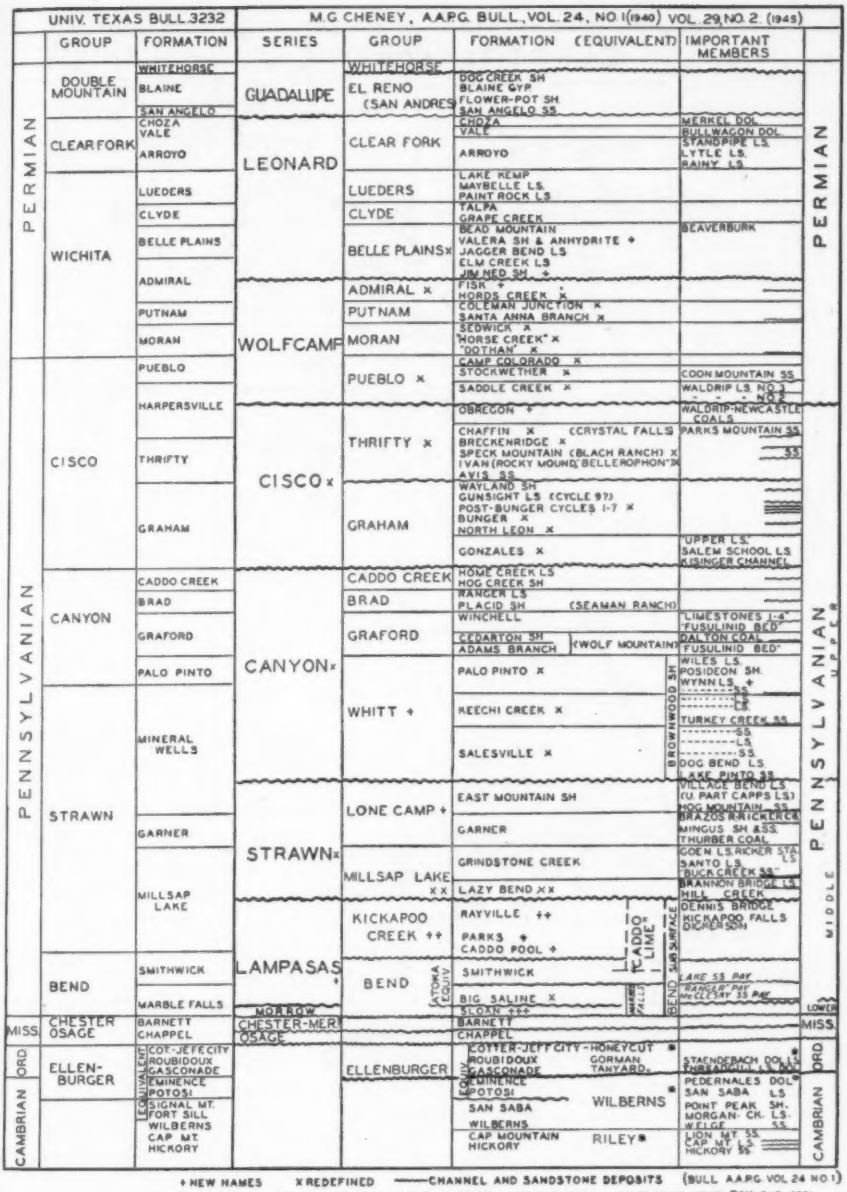
Since original publication of Chart I seven years ago, accumulating geological data appear to necessitate certain changes in the classification and correlation of the lower part of the Pennsylvanian section. As reported in 1945[9] fusulinids in cores from the uppermost "subsurface Bend" of Coleman County are similar to those found in the outcropping Dennis Bridge and Kickapoo Falls limestones of southwestern Parker and northwestern Hood counties. They indicate approximate time equivalence of these beds with upper Dornick Hills and Savanna-Boggy divisions of Oklahoma,

[7] "Technique of Stratigraphic Nomenclature," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIV (1940), pp. 2038–48.

[8] E. H. Sellards, "The Geology of Texas. Vol. I," *Univ. Tex. Bull. 3232* (1932), pp. 98–115.

[9] Pp. 162–63 of ftn. 2.

CHART I



+ NEW NAMES x REDEFINED ——CHANNEL AND SANDSTONE DEPOSITS (BULL. A.A.P.G. VOL. 24 NO. 1)

* CAMBRIAN ORDOVICIAN OF CLOUD, BARNES AND BRIDGE JUNE 1945 UNIV. TEX. PUB. 4301

++ REVISED DEC. 1946, MGC. +++ F.B. PLUMMER UNIV. TEX. PUB. 4401

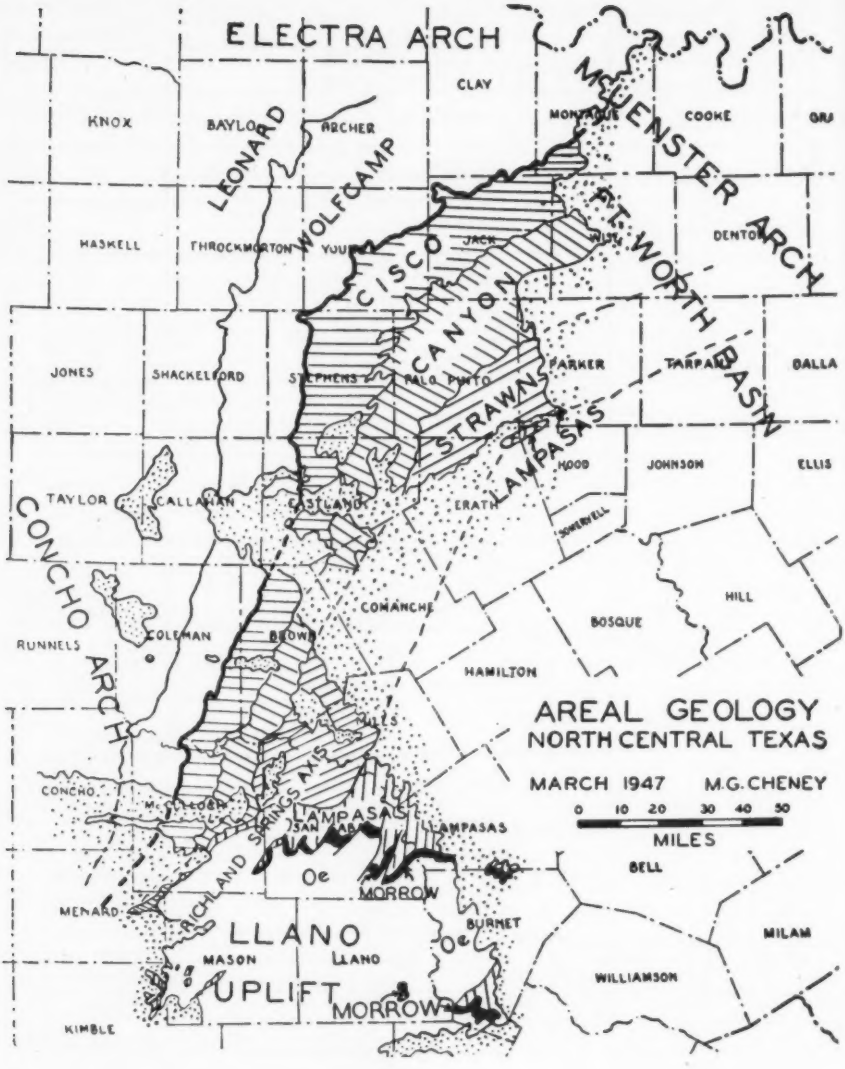

ELECTRA ARCH
KNOX
BAYLOR
ARCHER
CLAY
MONTAGUE
COOKE
GRA
LEONARD
WOLFCAMP
MUENSTER ARCH
HASKELL
THROCKMORTON
YOUNG
JACK
WISE
DENTON
CISCO
CANYON
FT. WORTH BASIN
JONES
SHACKELFORD
STEPHENS
PALO PINTO
PARKER
TARRANT
DALLAS
STRAWN
LAMPASAS
HOOD
JOHNSON
ELLIS
TAYLOR
CALLAHAN
EASTLAND
ERATH
SOMERVELL
CONCHO ARCH
COMANCHE
BOSQUE
HILL
RUNNELS
COLEMAN
BROWN
HAMILTON
AREAL GEOLOGY
NORTH CENTRAL TEXAS
MARCH 1947 M.G. CHENEY
0 10 20 30 40 50
MILES
CONCHO
MILLS
LAMPASAS
SAN SABA
LAMPASAS
RICHLAND SPRINGS AXIS
BELL
Oe
MORROW
MENARD
LLANO
BURNET
Oe
MILAM
MASON
LLANO
UPLIFT
MORROW
WILLIAMSON
KIMBLE

FIG. 1

which, in turn, according to evidence of the fusulinids, brachiopods, and flora, are close time equivalents of the Upper Tradewater of Illinois and the Clarion sequence of eastern Ohio and western Pennsylvania.[10] Clarion beds have been classified as basal Allegheny by some, but as Upper Pottsville in more recent reports by G. H. Ashley, state geologist of Pennsylvania.[11] These considerations favor placing the Lampasas-Strawn series boundary at the disconformity between the Dennis Bridge limestone and the overlying conglomerate. When thus restricted, the Strawn series of the Brazos River section is about 2,000 feet thick, its two groups and four formations measuring approximately as follows:

Strawn Series	Feet
Lone Camp group:	
East Mountain shale formation	400
Garner formation	200
Millsap Lake group (restricted):	
Grindstone Creek formation	650
Lazy Bend formation (restricted)	750

A "Kickapoo Creek group" is now proposed for the section between Millsap Lake group (restricted) and the Bend group, in other words, from the disconformity at or near the top of the Dennis Bridge limestone down to the top of the Smithwick. This new name is derived from Kickapoo Creek of southwestern Parker and northwestern Hood counties, Texas. The upper 200 feet, more or less, of this group outcrops between the villages of Dennis and Lipan. However, the Kickapoo Creek group must be studied mostly from well samples. Data from wells indicate that approximately 2,600 feet of the section should be assigned to this group in southwestern Parker County, 3,500 feet or more in the Fort Worth Basin.

Logs of the Gilbert No. 1 and Wheeler No. 1 wells of southwestern Parker County, 5 miles north-nourtheast of Lipan, were shown in a cross section published in 1945[12] and are here reproduced in modified outline as Figure 2.

The stratigraphic section assigned to the Kickapoo Creek group includes the Rayville (new name defined below), Parks, and Caddo Pool formations, which extend from depths of approximately 380–1,350, 1,350–2,125, and 2,125–3,000 feet, respectively, in these wells. It seems appropriate to refer to the Kickapoo Creek group as "Upper Lampasas" and the Smithwick and Big Saline formations as "Lower Lampasas."

As tentatively correlated with the more clastic Colorado River outcrop section, 100 miles to the southwest, the Kickapoo Creek group includes Drake's Lynch Creek beds (No. 4) up to the top of the thick, "blackish" shales of the Big Valley beds (No. 12), a total thickness of about 2,000 feet.[13] The equivalent in the McAlester Basin of Oklahoma is thought to extend from the top of the Atoka to the top of the Boggy, with maximum thickness of about 7,000 feet. The Kickapoo Creek group is now proposed in preference to the elevation of Parks formation to Parks group, as suggested in 1945.[14] Evidently, the uppermost part of the Caddo limestone in Coleman and Brown counties is somewhat younger than the limestones and shales heretofore classified as the Parks formation in Young and Stephens coun-

[10] *Ibid.*, pp. 146–56.

[11] "The Pittsburgh-Pottsville Boundary," *Jour. Geol.*, Vol. LIII (1945), pp. 374–89; see also ftn. 1 above.

[12] Fig. 2, pp. 154–55 of ftn. 1.

[13] N. F. Drake, "Report on the Colorado Coal Field of Texas," *Tex. Geol. Surv., Fourth Ann. Rept.* (1893), reprinted as *Univ. Tex. Bull. 1755* (1917), pp. 17–21.

[14] Pp. 163–64 of ftn. 1.

ties. The Caddo Pool formation is apparently assignable to the Kickapoo Creek group, according to evidence reported by Spivey and Roberts.[15]

The name "Rayville formation" is here proposed for beds from the disconformity just above the Dennis Bridge limestone down to the top of the Parks formation. It includes a total thickness of approximately 1,000 feet of alternating limestone, blue and black shales, and sandstones in the type locality of southwestern Parker County. The name "Rayville" is derived from an early settlement, now almost abandoned, located 3.4 miles southwest of Dennis and a like distance northeast of Kickapoo Falls. Important outcropping members include the Dennis Bridge limestone; an un-

[15] P. 183 of ftn. 6.

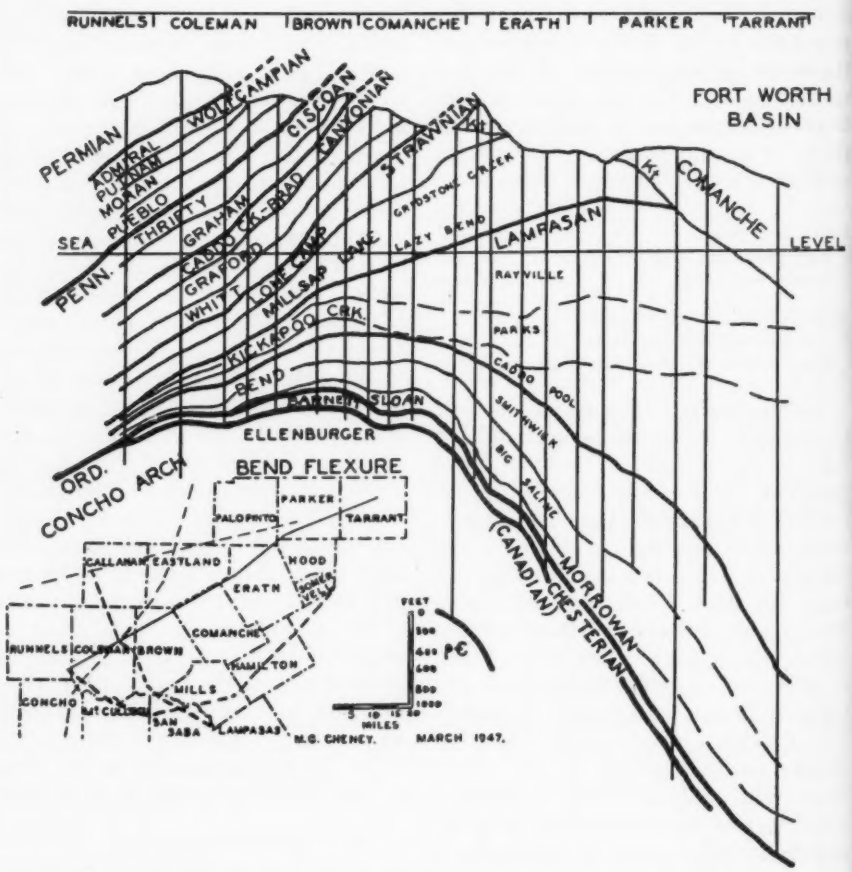


FIG. 2.—Profile from Concho arch to Fort Worth basin, showing time-stratigraphic divisions of system and series rank; also lithologic groups and certain formational units from Middle Strawn to the Upper Mississippian Barnett shale and Lower Ordovician Ellenburger limestone (see *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIX [1945], pp. 154–55, for stratigraphic details).

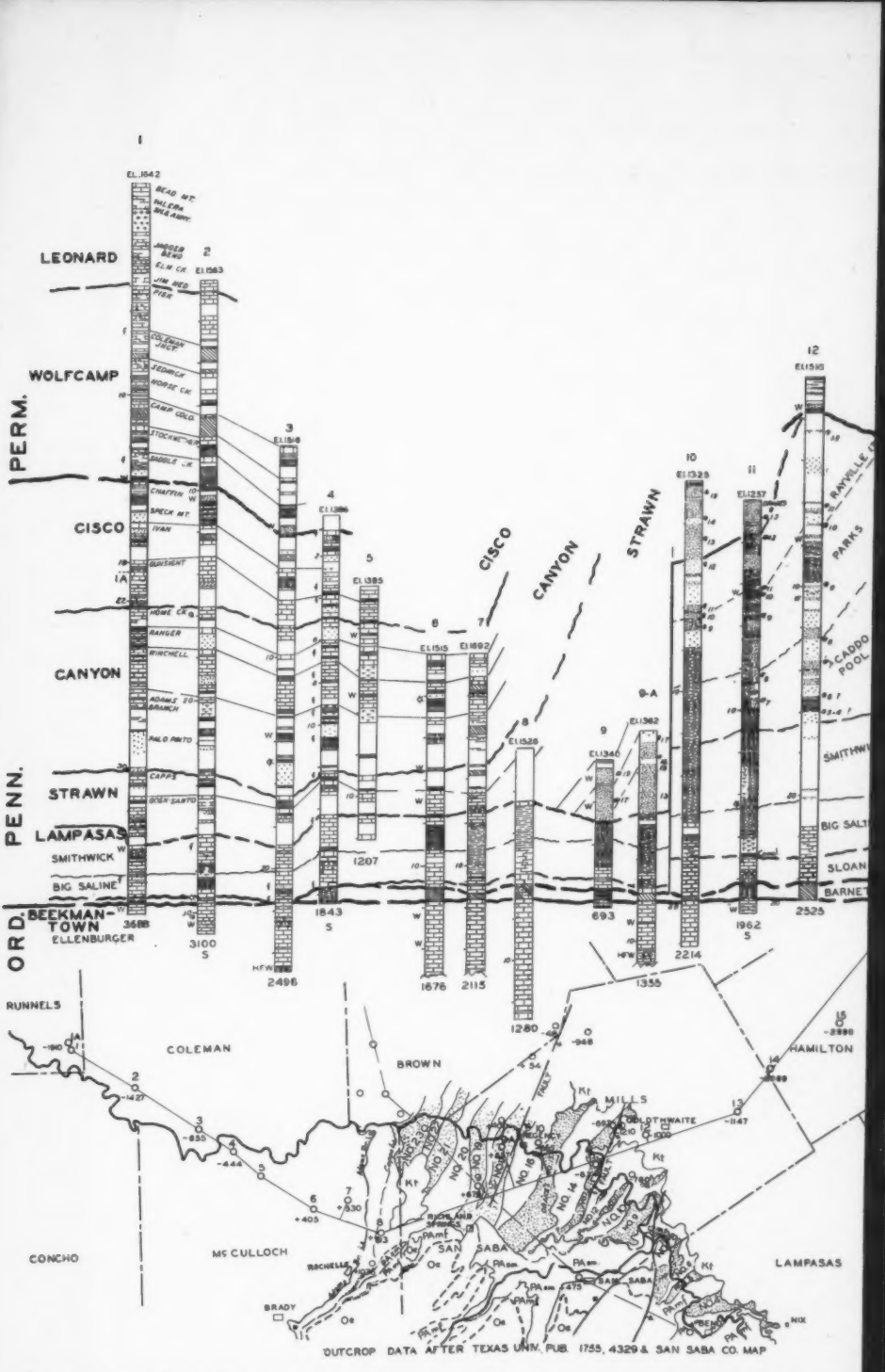
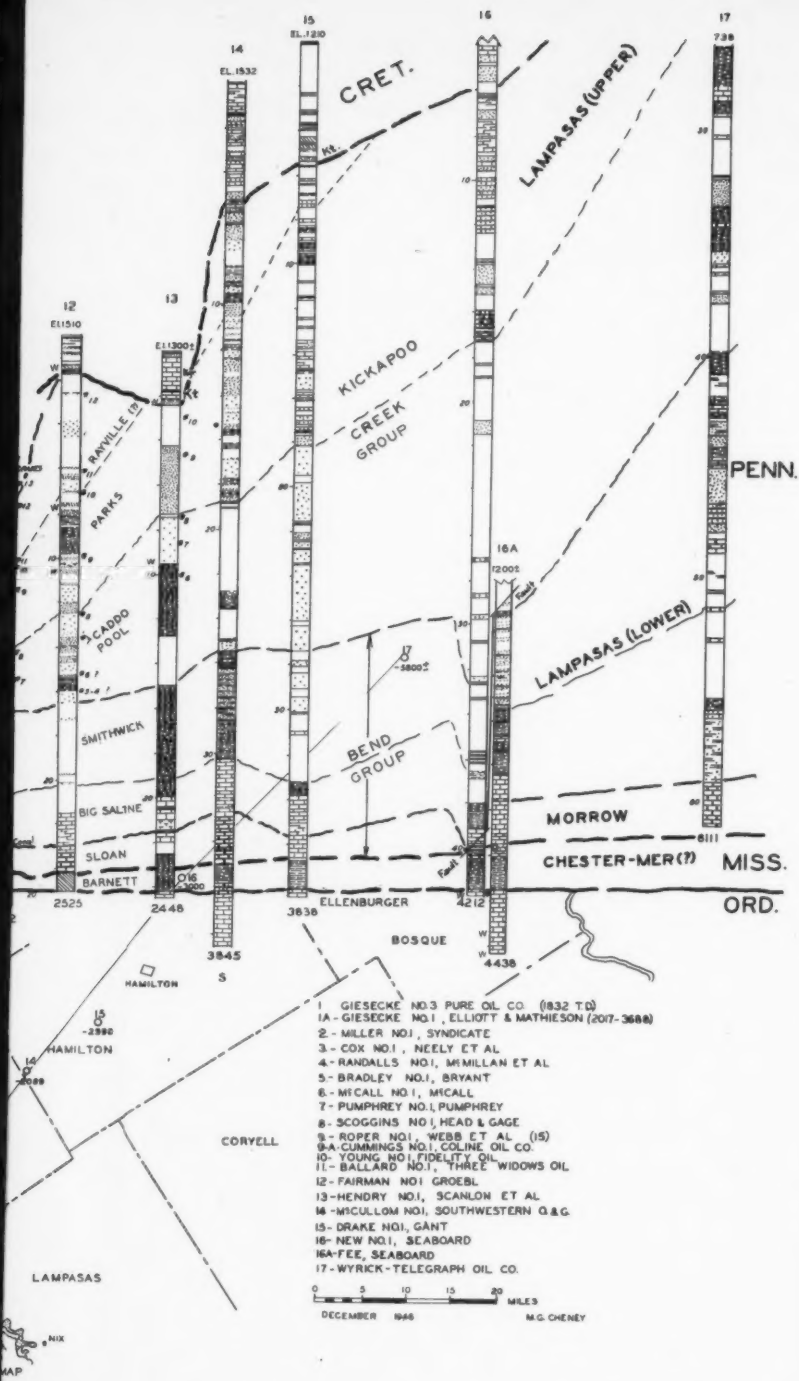


FIG. 3.—Cross section from Bosque to Runnels counties showing; *1*, westward loss by thinning, faulting, and tr of 110 miles; *2*, outcrop data of the San Saba district; *3*, elevations for top of Ellenburger; *4*, northeast trending time; *5*, fault cut by wells *16* and *16A*, with displacement of 500 feet or more, according to seismograph work.



faulting, and truncation of 3,000 feet of Upper Lampasas and Lower Strawn series in a distance theast trending fault between wells *9A* and *10*, evidently developed near the close of Lampasas nograph work.

named 100–125-foot section of shale, dolomitic limestones, and sandstone; the Kickapoo Creek limestone; and the Dickerson shale—a combined thickness of about 200 feet. Prior publications have given brief descriptions and partially recorded the faunas of these beds.[16]

The Rayville formation thins rapidly westward from its type area, being less than 300 feet thick in Brown and Coleman counties. This formation is absent over the more positive areas, such as the Richland Springs axis, the southeastern part of the Concho arch, and the Electra and Muenster arches.

The general character and thickness of the Lampasas series of the Colorado River district is shown in Figure 3, which also illustrates its unconformable relationships with both the overlying Strawn series and the underlying Morrowan. The late Dr. F. B. Plummer assigned the name "Sloan"[17] to the outcropping Morrowan rocks, and this name should now replace the subsurface name "Comyn."

The name "Mable Falls limestone" apparently is too fixed and useful as a broad lithologic term for the Sloan and Big Saline limestone sequence to be restricted to limestones either above or below the Morrow-Lampasas series boundary. This is also true for the name "Bend group." When applied to the outcrop section, the Bend group generally includes the Sloan, Big Saline, and Smithwick. Traced underground, each of these three divisions shows sufficient rock diversity and thickness to qualify as a mappable unit. No less than formational rank is thought to be appropriate for each.

[16] Frederick B. Plummer and Raymond C. Moore, "Stratigraphy of the Pennsylvanian Formations of North-central Texas," *Univ. Tex. Bull. 2132* (1921), pp. 70–74; F. B. Plummer and J. Hornberger, Jr., "Geology of Palo Pinto County," *Univ. Tex. Bull. 3534* (1935), pp. 15–16, 19–20; Carl O. Dunbar, Lloyd G. Henbest, and J. Marvin Weller, "Pennsylvanian Fusulinidae of Illinois," *Ill. Geol. Surv. Bull. 67* (1942), pp. 113–15.

[17] "Stratigraphy of Lower Pennsylvanian Coral-bearing Strata of Texas," *Univ. Tex. Pub. 4401* (1944), pp. 66–68.

LOWER PENNSYLVANIAN

Rocks of Springer age have not been recognized at the surface in north-central Texas; those correlated with the Morrow crop out only in the eastern two-thirds of the Llano Uplift region. Recent studies of fusulinids[18] and corals[19] indicate that the upper part of the type Marble Falls and Bend divisions are Lampasan and the basal part Morrowan.

MIDDLE PENNSYLVANIAN

Separation of Sloan and Big Saline beds is difficult in areas of outcrop, because the boundary commonly falls within a limestone sequence. However, to the north and northwest, wells in many areas have disclosed the presence of chert conglomerates or coarse sandstone lenses beneath *Fusulinella*-bearing beds of the Big Saline and above oölitic or dense Pennsylvanian limestones, in which *Fusulinella* are not found. This conglomerate and sandstone zone expands northward and is correlated with the Bend conglomerate pay zone of Montague County and the Bostwick conglomerate of the Ardmore Basin in southern Oklahoma. A considerable thickness of Dornick Hills beds below the Bostwick is generally accepted as belonging to the Morrow series.

[18] M. L. Thompson, "Stratigraphy and Fusulinids of Pre-Desmoinesian Pennsylvanian Rocks, Llano Uplift, Texas," *Jour. Paleon.*, Vol. XXI (1947), pp. 147–64.

[19] Raymond C. Moore and Russell M. Jeffords, "Description of Lower Pennsylvanian Corals from Texas and Adjacent States," *Univ. Tex. Pub. 4401* (1944), pp. 77–81.

Black shales and thin limestones of Upper Big Saline age, below the olive-brown and upper black shales of the Smithwick, occur in isolated areas on the eastern and northeastern flank of the Llano Uplift and are typically developed near the village of Bend. The Caddo limestone facies of the upper "subsurface Bend" or Kickapoo Creek group extends westward from Brown, Eastland, Stephens, Young, and Jack counties. Well data show that these limestone beds grade to shale eastward. The eastern margin of this limestone–dark shale transition belt can be traced as far south as northeastern McCulloch County in the subsurface. This shale is absent, presumably by erosion, over the Richland Springs axis but reappears as a shale and sandstone sequence farther east, as shown in wells 10–17 of Figure 3.

Figure 3 also illustrates (1) the westward loss of rocks of Morrow and Springer ages, as proved by the contact of *Fusulinella*-bearing beds with Mississippian and Ordovician in well 4 and westward; (2) the variable lithologic character of the Big Saline and Smithwick formations; (3) pronounced changes in thickness of Upper Lampasas rocks as a result of structural changes near the close of Lampasan time; (4) evidence that the pronounced Llano fault system, which extends northeastward beneath the Strawn series, was developed near the close of Kickapoo Creek time and prior to deposition of the thick sandstones found in the upper part of wells 9–11 of Figure 3. As traced northward and eastward in wells, these sandstones belong to the Millsap Lake group (restricted).

The progressive overlap observed in outcrops in San Saba County extends southwestward across McCulloch to eastern Menard and Kimble counties. Strawn and Lower and Middle Canyon beds rest on Big Saline and Ellenburger limestones over the Concho arch around the western border of the present Llano Uplift.

The outcropping and subsurface Upper Lampasas beds show very different facies, according to correlations derived from Figures 3 and 4 and other regional studies.

The clastics deposited east of the Richland Springs axis probably came from the southwestern extension of the folded and uplifted Ouachita trough, with its thick sandstone, shale, and chert sequence, whereas the calcareous sediments in the V-shaped area northwest from the Richland Springs axis and northeast from the Concho arch may represent deposition on a bank or shallow platform near the mouth of northward drainage from Ellenburger limestone and dolomite surfaces which were undergoing gradual elevation along these two broad structural axes. Major faults ing and uplift of these axes appear to have occurred near the close of Lampasa-time.

Subsurface studies show that the Richland Springs axis is part of an extensive anticline which developed mainly during pre-Strawn time across what is now Mason, McCulloch, and San Saba counties to central Brown County. Farther northward this anticlinal axis became a flexure. This conclusion is based on loss of Upper Lampasas and Lower Strawn in the southern part of this major structural trend and upon no such loss of section in the northern part. Distinctive names may prove useful for different parts of this extensive feature, as follows: (1) "Richland Springs axis" for that part which may be seen at the surface in western San Saba County and for 50 miles to the southwest; (2) "Bend

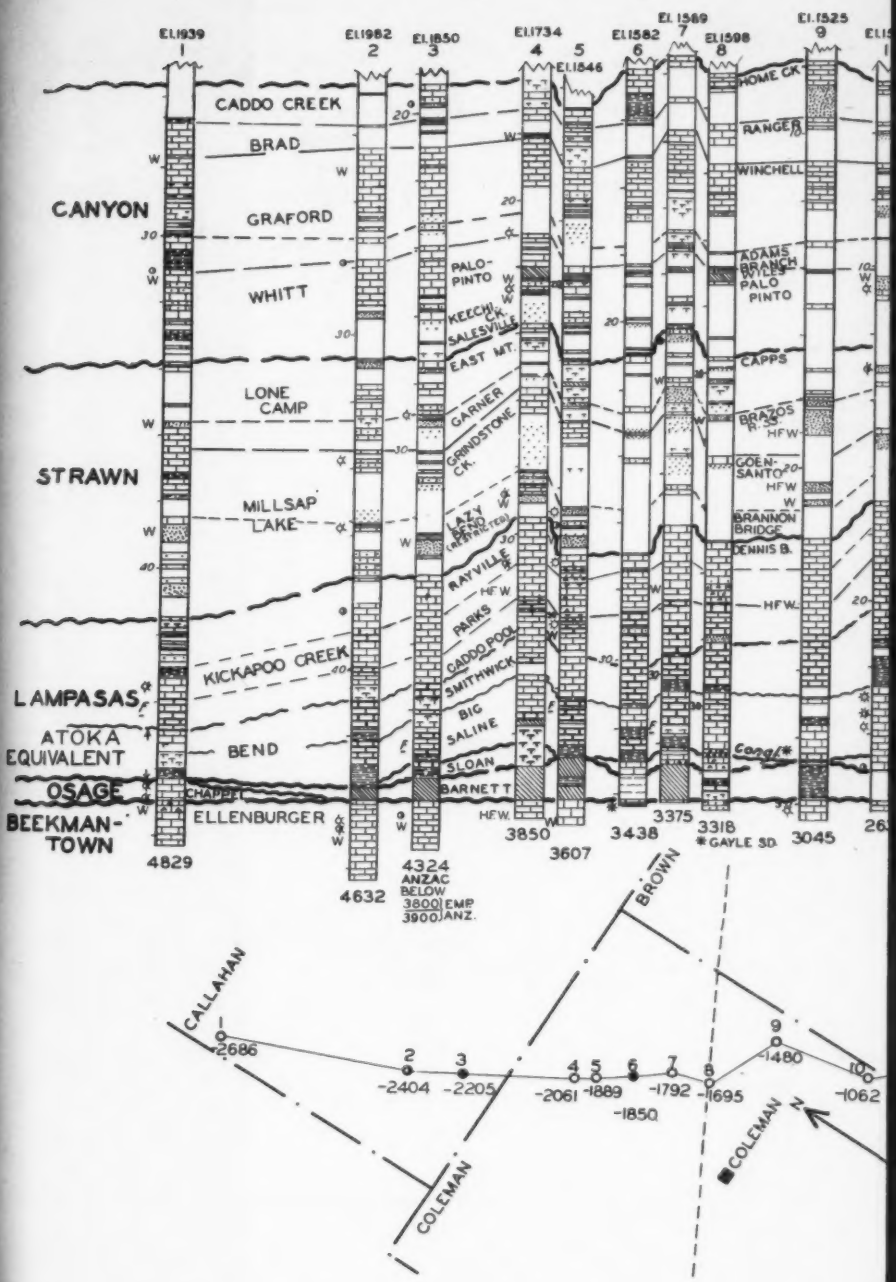
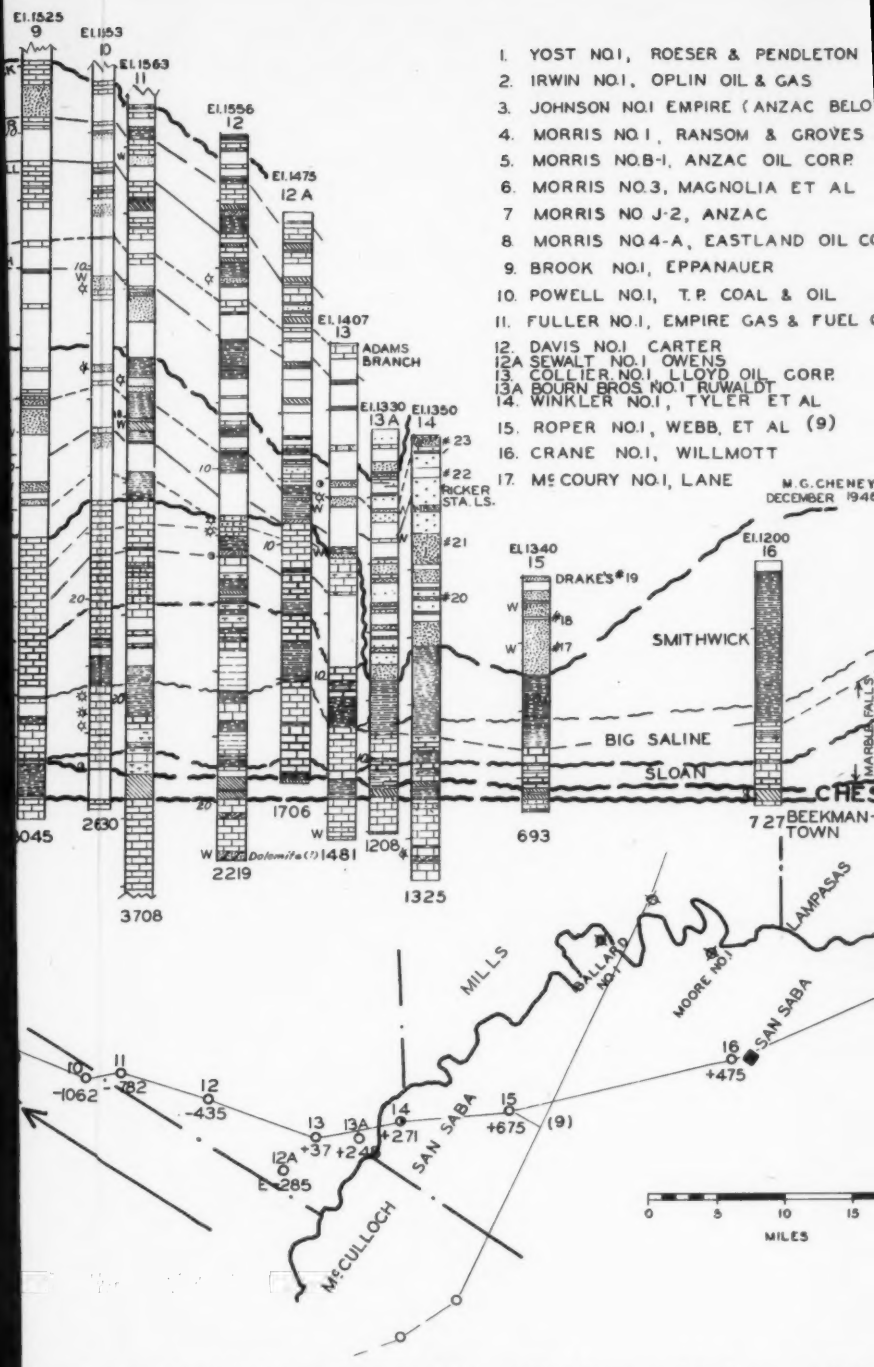


FIG. 4.—This cross section extends northwest 120 miles from the type locality of the Bend group. Litholog area (Wells *1–13*). Post-Lampasas uplift and erosion are indicated; also unconformities between Lampasas, map. No faulting is indicated between wells *12-A* and *14*, where abrupt lithologic changes occur.



. Lithologic similarity of the Kickapoo Creek, Smithwick, and Big Saline strata of the Lampasas series is
Lampasas, Morrow, and Strawn series. Sea-level position of the Ellenburger surface is placed beneath w
f.

PENDLETON
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& GROVES
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CORP.
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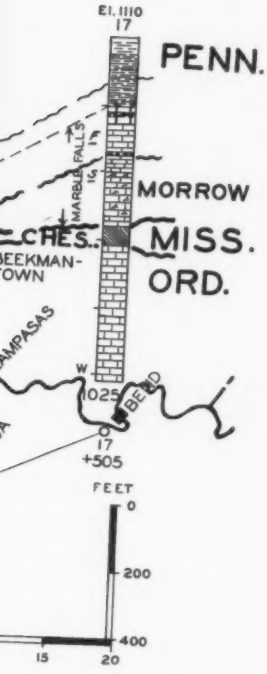
M. G. CHENEY
CEMBER 1946



eries is evident over a large
neath well symbols on the .

arch" for the subsurface feature which developed as an arch for a distance of about 30 miles from the Richland Springs to the Brownwood district; and (3) "Bend flexure" for 120 miles northward from the Brownwood district, the present arched appearance of the Bend flexure having resulted from westward tilting during post-Pennsylvanian time.

As previously reported,[20] fusulinids from the Upper Caddo or "subsurface Bend" limestone in Coleman County indicate time equivalence with the Kickapoo Falls and Dennis Bridge limestones. As traced northward in wells, the Big Valley member (No. 12) of the Colorado outcrop section appears correlative with the Kickapoo Creek group. The area in which Upper Lampasas muds or shales were eroded and replaced by Strawn sands extends over several hundred square miles west of the major rifting and in trend with the pronounced Richland Springs structural axis. These data support the conclusion that considerable uplift and erosion must have taken place in north-central Texas near the close of the Lampasas epoch. Similar structural developments evidently occurred in eastern Oklahoma, where the Boggy, but not higher beds, was affected by the closing phases of the Ouachita orogeny. The Boggy beds are involved in pronounced northeast-trending faults with displacements up to 600 feet, as at Muskogee,[21] and sharp folds with dips of more than 20 degrees in the McAlester Basin. Choice of a basal boundary for the Des Moines series should depend in part on the structural history of the Mid-Continent region. The analysis by Shepard W. Lowman[22] deserves repeating:

Basal Marmaton
Upper Cherokee: Calvin Sandstone—Thurman sandstone
Middle Cherokee: Boggy formation—Lower Savanna sandstone
Lower Cherokee: McAlester shale—Atoka formation

Major changes in the regional structure of the mid-continent area seem to have been initiated between the middle and upper Cherokee as evidenced by the following data:

1, There is a broad regional unconformity at the base of the upper Cherokee. 2, Comparatively coarse sediments in the Chelsea-Thurman sandstone grade rapidly into finer sediments in the underground to the west indicating that the present line along which these sediments crop out is near their original shore line. 3, The area of maximum sedimentation in the upper Cherokee shifts many miles northwest of the axis of the middle and lower Cherokee basins. 4, The line of strike changes with the advent of the Thurman. 5, The folds of the "Brown lime" (note: upper Savanna) in the Seminole area show that the folding during middle Cherokee time was in phase with lower Cherokee. On the other hand the structural expression of the "Senora lime" (upper Cherokee) is disconformable with the middle and lower Cherokee. 6, The southwestern extension of the Ozark Mountains into Oklahoma appears to have been elevated in upper Cherokee time. 7, Continued uplift of many and possibly all major local uplifts seem to have persisted with diminishing intensity through upper Cherokee time and on through Marmaton, Kansas City, Lansing, and Douglas time and many of the structures are well expressed in surface strata as young as Permian. However, the regional structures like the Henryetta Flexure and the Central Oklahoma arch appear to have ceased moving with the end of the middle Cherokee time and all local folds are buried by upper Cherokee sediments. . . . .

The Hunton arch (proper) with attendant features such as the Henryetta Flexure, the Seminole Uplift, the Paul's Valley Arch, and the Central Oklahoma Arch and almost all important local "structures" had received their

[20] P. 162 of ftn. 2.

[21] Charles W. Wilson, Jr., and Norman D. Newell, "Geology of the Muskogee-Porum District, Oklahoma," *Okla. Geol. Surv. Bull. 57* (1937), p. 80.

[22] "Cherokee Structural History in Oklahoma," *Tulsa Geol. Soc. Digest* (1933), pp. 31 and 34.

essential form by the end of the Middle Cherokee time and were only modified by later events.

The Upper Cherokee and Marmaton are thought to be equivalent to the 2,000-foot section extending from the top of the Dennis Bridge limestone to the top of the East Mountain shale of the Brazos River district in north-central Texas. The Brannon Bridge, Santo, Goen, and Capps limestone members of this section show greatest lateral persistency. The genus *Wedekindellina* is rare or absent in the Goen limestone and higher beds, according to several fusulinid specialists. Previous extensive studies of the Strawn have solved many of the earlier problems of correlation, although doubtless much more remains to be learned about faunal zones, lithologic changes, and how much and what part of the loss of section in the more positive areas was caused (1) by lateral thinning when deposition was going on or (2) by truncation following uplift.

UPPER PENNSYLVANIAN

Most limestone members of the Canyon and Cisco series show considerable persistency in outcrop and subsurface. Where these Upper Pennsylvanian rocks crop out, the Comanche overlap narrows sufficiently to permit nearly continuous mapping of individual members across north-central Texas. Tracing by Plummer and Moore of the Home Creek limestone northward from its type area is believed to be more correct than the more recent interpretation by W. Lee and C. O. Nickell.[23] Other problems of the Upper Pennsylvanian are discussed below.

[23] "Stratigraphic and Paleontologic Studies of the Pennsylvanian and Permian Rocks in North-central Texas," *Univ. Tex. Pub. 3801* (1938), pp. 108–17, Pl. VIII.

SUBSURFACE STRATIGRAPHY

Classification and correlation studies of the subsurface Pennsylvanian rocks in north-central Texas must deal with a composite section about 10,000 feet thick,[24] as against 5,000 feet for the exposed sections and about 1,000 feet over the Concho, Electra, and Muenster arches. Pennsylvanian rocks outcrop or are reached at a depth of less than 1 mile throughout an area of about 70,000 square miles. Subsurface rock samples are available from many of the tens of thousands of wells drilled for petroleum in this region.

LOWER PENNSYLVANIAN

Rocks of Springer age have been identified in well cuttings by H. D. Miser and E. H. Sellards[25] in the extreme eastern portion of this region, evidently proving that the early Pennsylvanian Ouachita Basin of southeastern Oklahoma extended southwestward into Texas. Quite possibly this deeply subsiding trough continued around the Concho arch to connect with the Tesnus trough of the Marathon region. The Springer series is thought to be of the same age as the Pocahontas series (Lower Pottsville) of the northern Appalachian standard section.

The Sloan formation of Morrow age is present in the basin areas and over the Bend flexure (or arch) but is absent over the Concho, Electra, and Muenster arches.

[24] Pp. 154–55 and Fig. 2 of ftn. 1.

[25] "Pre-Cretaceous Rocks Found in Wells in Gulf Coastal Plain South of Ouachita Mountains," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XV (1931), pp. 801–18; E. H. Sellards, "Rocks Underlying Cretaceous in Balcones Fault Zone of Central Texas," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XV (1931), pp. 819–27.

As previously stated, the original usage of the name "Marble Falls limestone" as defined by Hill may well be retained as a broad lithologic term to be used where differentiation into Sloan and Big Saline is not established. The Morrow series is closely equivalent to the New River series (Middle Pottsville) of the northern Appalachian standard section.

MIDDLE PENNSYLVANIAN

The two most significant and pronounced changes in the Pennsylvanian fauna in the Mid-Continent occur at the Morrow-Lampasas and the Des Moines–Missouri series boundaries. The strata between these two outstanding boundaries attain a thickness of at least 15,000 feet in the McAlester and Atoka basins in southeastern Oklahoma. It is now generally accepted that this thick section should be divided into two series rather than be included in the Des Moines series, as was the custom until the late 1930's. The name "Winslow" was used to some extent for the Atoka plus a variable amount of overlying section but was formally discarded by the United States Geological Survey because of varied usage. Many geologists in Oklahoma have expressed objection to the revival of "Winslow" as the name for a series between the Morrow and the Des Moines series. As early as 1935 some unpublished reports began dividing this thick section into Atoka and Des Moines series because of faunal, lithologic, and structural changes at the top of the Atoka. Apparently, the first proposal of two series to appear in formal literature was in 1940 when the name "Lampasas" was introduced for a post-Morrow–pre-Des Moines series.[26]

[26] Pp. 81–87, Fig. 1, of ftn. 5.

Doubtless, the identification[27] of plants of the *Neuropteris rarinervis* zone of Clarion age in the Hartshorne-Boggy formations played some part in the inclusion of these post-Atoka beds in the Des Moines series, because most of the Clarion rocks were then commonly included in the Allegheny division in Pennsylvania and Ohio. The recently expressed preference by the state geologist of Pennsylvania and paleobotanical specialists for an Allegheny-Kanawha (Upper Pottsville) boundary at or very near the top of the Clarion beds supports the selection of a comparable boundary higher than the top of Atoka in the Mid-Continent region.

The Lampasas series, as defined for north-central Texas, was thought properly to include all post-Morrow rocks commonly assigned to the Bend group of the subsurface. Geological literature is replete with papers dealing with the geology of the pre-Strawn gray and black limestone and black shale sequence of the subsurface.[28] It was recognized that the 600-foot upper limestone section of this 1,200-foot sequence changes eastward

[27] T. A. Hendricks and C. B. Read, "Correlations of Pennsylvanian Strata in Arkansas and Oklahoma Coal Fields," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XVIII (1934), p. 1046 n.

[28] Wallace E. Pratt, "Geologic Structures and Producing Areas in North Texas Petroleum Fields," *Bull. Amer. Assoc. Pet. Geol.*, Vol. III (1919), pp. 44–70; W. G. Matteson, "A Review of the Development in the New Central Texas Oil Fields during 1918," *Bull. Amer. Assoc. Pet. Geol.*, Vol. III (1919), pp. 163–211; Plummer and Moore, p. 42, Pl. 5, of ftn. 16; E. K. Esgen, "Relation of Accumulation of Petroleum to Structure in Stephens County, Texas," *Structure of Typical American Oil Fields*, Vol. II (Amer. Assoc. Pet. Geol., 1929), pp. 470–79; Frank E. Kendrick and Philip G. Russell, "Natural Gas in Bend Arch District, Texas," *Geology of Natural Gas* (Amer. Assoc. Pet. Geol., 1935), pp. 609–49; Fort Worth Geological Society, H. H. Bradfield, *et al.*, "Geologic Cross-Section of North-central Texas" (Dec. 21, 1940).

into black and dark shales, whereas westward it is much reduced in thickness by thinning and truncation toward the Concho arch. Likewise, it has been widely held that the structural features of these subsurface Bend rocks differ notably from those observed in overlying beds. Thus many writers believed that important differences of lithology and structure clearly differentiated the Caddo limestone and black-shale section from the overlying sandstones and shales with some interbedded limestones, which typify the Strawn division.

In recent years fusulinid specialists have noted the presence of *Wedekindellina* and early types of *Fusulina* s.s. in the Caddo limestone and have recommended extending the Strawn series down to the base of the Caddo Pool formation. In accordance with this view, Spivey and Roberts have presented a strong case for an Atoka series in both Oklahoma and north-central Texas.[29] There are, however, objections to the suitability of the Atoka because of structural complications in the type area. Also earliest representatives of *Wedekindellina* and *Fusulina* occur in the Owens-Frensley beds of the Ardmore Basin, probably correlative with the Red Oak zone, 500 feet below the top of the Atoka.[30] Upper Kanawha and Tradewater beds of the Appalachian and Illinois basins are doubtless of post-Atoka age.

Perhaps a portion of the outcropping Upper Smithwick shale near Smithwick may be equivalent to the siliceous Caddo Pool formation of the subsurface. The Smithwick increases in thickness eastward and becomes much more sandy near its original type locality than in areas farther west and northwest.

The predominantly limestone development of the Kickapoo Creek group in the Bend flexure region seems to be an example of biostrome development.[31] These rocks have yielded more than 200,000,000 barrels of oil in Stephens, Young, Shackelford, Eastland, and adjoining counties.

The name "Bend" was used in formal literature from the 1890's to about 1918 to designate outcropping rocks ranging from the base of the Barnett to the top of the Smithwick. Since 1918 it has been applied the Marble Falls and Smithwick of the outcrop, and in the subsurface to the Mable Falls, Smithwick, and younger strata now assigned to the Kickapoo Creek group. Recently, the use of "Bend" as a series name restricted to the Big Saline and Smithwick of the outcrop section has been advocated.[32] Thus the names "Winslow," "Atoka," "Lampasas," and "Bend" have been advocated for a post-Morrow–pre-Des Moines series in the Mid-Continent region. The best solution of these conflicting views and usages is not readily apparent. However, if the Clarion rocks of the type Pennsylvanian section are assigned to the Kanawha series then the "Lampasas series," as used herein, is to be preferred on the basis of time equivalency as judged by present paleontologic evidence.

The type Kanawha division of West Virginia has, for the last forty years, included in its upper part the Kanawha black flint and Roaring Creek sandstone, which H. R. Wanless[33] tentatively

[29] Pp. 185–86 of ftn. 6.

[30] H. H. Bradfield, personal communication, January 15, 1947.

[31] E. R. Cumings, "Reef or Bioherms?" *Bull. Geol. Soc. Amer.*, Vol. XLIII (1922), pp. 331–52.

[32] P. 73 of ftn. 17.

[33] "Pennsylvanian Correlations in the Eastern Interior and Appalachian Coal Fields," *Geol. Soc. Amer. Spec. Paper 17* (1939), p. 50.

correlated with the Zaleski flint and Clarion sandstone, respectively, above the Putnam Hill limestone of eastern Ohio and western Pennsylvania. M. L. Thompson[34] reported *Fusulina leei*[35] in the Putnam Hill limestone and the transitional species, *Fusulinella* or *Fusulina carmani*, in the Vanport limestone which Ashley[36] places in the Pottsville. These or similar primitive *Fusulina* species occur in upper Tradewater and Boggy beds.

M. T. Sturgeon reports that the striated forms of *Mesolobus* extend up to, or nearly to, the Vanport limestone, whereas the smooth types appear abundantly in the Hamden limestone of the lower Kittanning section of eastern Ohio.[37] A. T. Cross has found that "megaspore assemblages" indicate that "major floristic changes" occur between the Coalburg and the Buffalo Creek coals of West Virginia, somewhat below the top of the Kanawha division.[38] According to Ashley's correlations,[39] this floral break is somewhat above the Brookville and below the Lower Kittanning coal of Beaver Valley, Pennsylvania.

Correlations of these rocks with the Illinois and Mid-Continent section have been made by plants, fusulinids, brachiopods, and other fossils. As previously stated, Read concluded that Clarion plants are present in the Hartshorne, McAlester, and Savanna and as high as studied in the Boggy of the McAlester Basin. No paleobotanical data seem to have been gathered for this part of the Pennsylvanian system in north-central Texas. Dunbar, Henbest, and Weller have reviewed correlations between the northern Appalachian region and Illinois based on fusulinids and other faunas.[40] They report that the advanced type of *Fusulinella—F. iowensis*—"appears to have a rather limited stratigraphic range," being "known only in Seville limestone in Illinois, at a single horizon in Iowa (90 feet below the Whitebreast coal) that is probably equivalent to the Seville, and in the Upper and Lower Mercer limestones of Ohio." The Mercer limestones have invariably been classified as Upper Pottsville in the Appalachian region. Species presumably included in the subzone *Fusulina leei* are recorded from the Clarion, Upper Tradewater, Savanna, Lower Boggy, Upper Dornick Hills, and Kickapoo Falls of Ohio, Illinois, Oklahoma, and north-central Texas, respectively. Only one species, *Wedekindellina euthysepta*, is shown in this report to cross the Tradewater-Carbondale boundary in Illinois.

It is doubtless significant that approximately equivalent boundaries near the middle of the Pennsylvanian system were chosen independently by early workers in the northern Appalachian, Illinois, Ardmore, and north-central Texas (subsurface) regions. Past differences in classification of this part of the section in the northern Mid-Continent may be attributed, perhaps, to the view that the Des Moines series by definition must include all pre-Missourian Pennsylvanian found in the Des Moines River region. However, the oldest Pennsylvanian rocks of the Des Moines River section contain fusulinids of the *F. iowensis* and *F. leei*

[34] "Pennsylvanian Fusulinids from Ohio," *Jour. Paleon.*, Vol. X (1936), pp. 677–79.

[35] Dunbar, Henbest, and Weller, p. 30, of ftn. 16.

[36] George H. Ashley, "The Pittsburgh-Pottsville Boundary," *Jour. Geol.*, Vol. XXIX (1945), pp. 125–69.

[37] "Allegheny Fossil Invertebrates from Eastern Ohio–Nautiloidea," *Jour. Paleon.*, Vol. XX (1946), pp. 11–12.

[38] "Spore Floras of the Pennsylvanian of West Virginia," *Bull. Geol. Soc. Amer.*, Vol. LVII (1946), p. 1265.

[39] Fig. 5, p. 381, of ftn. 11.

[40] Pp. 28–34 of ftn. 16.

subzones and other fauna characteristic of the Upper Pottsville. Therefore, it may prove more useful for purposes of interregional correlation to recognize the lower boundary of the Des Moines series in the northern Mid-Continent region as occurring between the zones of early and late types of *Fusulina* instead of between the restricted and advanced types of *Fusulinella*.

Drilling and geophysical work have revealed that Bend and older rocks in the subsurface are affected by an extensive system of normal faults or steep folds with northeast trends, like those observed at the surface in the Llano Uplift region. As previously mentioned, these structures resemble the northeast-trending fault system of the Muskogee, Oklahoma, district, where normal faults with as much as 600 feet of displacement cut the Bluejacket sandstone of the lower Boggy.[41] Upper Cherokee and Millsap Lake beds exhibit much less structural disturbance than do older rocks, and their structural features commonly trend northwest instead of northeast.

UPPER PENNSYLVANIAN

Correlations of Canyon and Cisco rocks throughout north-central Texas are well established, with the possible exception of the Home Creek limestone as noted above. Lowering of the basal Canyon boundary has been proposed in recent years to accomplish closer agreement with the Missouri–Des Moines boundary of the northern Mid-Continent region.

W. F. Cummins[42] quite logically drew a lithologic group boundary at the base of the thick Palo Pinto limestone in his early study of the Brazos River Valley section. Subsequently it has been found that this thick limestone grades into shale northward in the subsurface and southward in the outcrops of the Colorado River section. The Palo Pinto is not equivalent to the Capps limestone in the latter area, as formerly believed, but, if present, it occurs near the middle of the 300-foot Brownwood shale section. Representatives of the genera *Fusulina* and *Mesolobus* are present in the Capps limestone (but not much, if any, higher) in the Brownwood district. These Des Moines fossils occur only as high as the East Mountain shale of the Mineral Wells district. Obviously, a series boundary based on faunal changes and prominent disconformity can be far more useful for careful subsurface geological work than was the former lithologic boundary based on a limestone of rather local extent. Thus in the Mineral Wells district the base of the Lake Pinto conglomerate should serve as a Strawn-Canyon series boundary more satisfactorily than the base of the Palo Pinto limestone, some 500 feet higher in the section.

The long-established boundary between Canyon and Cisco beds apparently requires no revision in order to qualify these divisions as series rather than as groups. The Kisinger channel,[43] which cuts through the Home Creek and down to the Ranger limestone in southeastern Young County, is one of many indications of a pronounced hiatus subsequent to Home Creek deposition. Cavey red shales and numerous areas of truncation of the Home Creek beds occur widely in north-central Texas. Canyon and older beds below this hiatus tend to thicken eastward, whereas Lower Cisco beds thicken westward and northwest-

[41] Wilson and Newell, pp. 74–84 of ftn. 21.

[42] "Report on the Geology of Northwestern Texas," *Tex. Geol. Surv., 2d Ann. Rept.* (1890), Pls. XVI, XVIII.

[43] Lee and Nickell, pp. 12–16, Pl. IV, Fig. 2, of ftn. 23.

ward from its area of outcrop in the Colorado River Valley.

Like the subsurface Bend group, the Canyon series is characterized by extensive calcareous deposits, which are difficult to correlate in some localities because of rather abrupt transitions. Further studies are needed to understand more fully the localization of these limestone deposits. The 200-foot limestone of the Palo Pinto formation in the subsurface of Stephens County grades into shales in northern Young and southern Eastland County, but the somewhat younger 125-foot Winchell limestone of Brown and Eastland counties becomes very thin northward in Young County. The Ranger limestone is relatively thick near its outcrop from Wise to McCulloch counties, but it thins westward in many areas. The total thickness of the Canyon series is not particularly affected by these lithologic changes. More or less extensive bioherms or reefs are quite common and in some areas extend upward throughout much, or even all, of the Canyon section. Some of these thick, calcareous bodies are dolomitized, with sulphur water, oil, or gas filling the porous zones. Many calcareous deposits of the Canyon series appear to be so local as to qualify as bioherms, others sufficiently extensive to resemble the biostromes of the Upper Lampasas series. Canyon limestone rests on Upper Strawn limestones and is followed by Cisco limestones on the Petrolia Uplift of Clay County and westward along the Electra arch. In earlier correlations[44] the lower portion of Pennsylvanian reef deposits was misidentified as Ellenburger, which it overlies in the Petrolia and Electra districts. Farther southward the limestone masses do not appear to be closely related to local structural features. They were evidently developed in shallow seas on banks or slightly raised platforms considerably removed from sources of clastic material. The seas of Canyon times covered all the more positive areas of north-central Texas, including the Muenster, Electra, and Concho arches.

Downward revision of the upper boundary of the Cisco series and Pennsylvanian system appears desirable, in order to reach agreement with the Permian boundary established in West Texas and elsewhere.[45] Permian schwagerinids occur down to, or perhaps even below, the Waldrip No. 2 limestone. Pronounced channels between several marine limestone members occur in this part of the section, indicating that elsewhere marked crustal disturbance was in progress, presumably the late Marathon thrust movements and the concluding phases of the Arbuckle-Wichita orogeny, which had been active during much of Cisco time.

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[44] M. G. Cheney, "Stratigraphic and Structural Studies in Northcentral Texas," *Univ. Tex. Bull. 2913* (1929), Pl. V.

[45] C. W. Tomlinson *et al.*, "Classification of Permian Rocks," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIV (1940), pp. 337–42, 352–54.

DISTRIBUTION AND CORRELATION OF PENNSYLVANIAN ROCKS IN LATE PALEOZOIC SEDIMENTARY BASINS OF NORTHERN NEW MEXICO[1]

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ABSTRACT

The most useful classification of the Pennsylvania series in northern New Mexico is by the lithologic character of the rocks, supplemented by paleontologic data where available. Few of the boundaries are sharp. The strata represent a single major sedimentary cycle, comprising, in ascending order, a suite of transgressive sediments, a widely distributed marine phase, and an unevenly distributed regressive phase, followed by continental sediments. For the marine part of the sequence the term "Magdalena group" is used, including the Sandia formation and the Madera limestone, the latter containing several named members. The positions of major positive areas and of depositional basins, total thicknesses, and general character of the sediments are indicated on a map of northern New Mexico, and detailed local sections are shown graphically in several charts.

INTRODUCTION

Field parties of the U.S. Geological Survey have been engaged in mapping parts of northern New Mexico for several years, much of the work being in areas of exposure of Pennsylvanian strata. The combined projects have covered approximately 16,000 square miles, and investigations are still in progress. This report is intended to summarize progress to date but is not a valedictory on the Pennsylvanian series in northern New Mexico.

The following individuals have participated with the authors in the investigations in New Mexico as geologists of the Geological Survey: Ernest Dobrovolny, V. C. Kelley, A. J. MacAlpin, S. A. Northrop, C. P. Rogers, Jr., H. H. Sullwold, Jr., C. H. Summerson, and R. H. Wilpolt. In addition, R. L. Bates and Georges Vorbe, of the New Mexico Bureau of Mines and Mineral Resources, have actively co-operated in several of the investigations and have offered much valuable counsel.

[1] Published by permission of the director, U.S. Geological Survey.

THE PENNSYLVANIAN SERIES IN NORTHERN NEW MEXICO

The Pennsylvanian series in New Mexico is composed of a complex sequence of marine and continental strata that has a lobate geographic distribution as a result of the presence of several Pennsylvanian positive elements. The rocks are exposed in belts of outcrop in and adjacent to the principal mountain ranges of the state and are known to be present at depth under several of the intermountain valleys, as well as under portions of the Colorado Plateau and High Plains provinces.

Regional analysis of the Pennsylvanian series in New Mexico has required much preliminary planning. The results of the work directly reflect these plans, and we think it essential for a proper understanding of the ensuing discussion to disgress briefly from our main objective to present our approach to the problem.

METHODS OF STUDY

Proper planning of a regional study consists in defining the objectives, determining the critical and the secondary

areas, and reaching decisions on methods and classifications to be used. It was clear that the principal objective for the purposes of this report was a study of the regional distribution and stratigraphy of the Pennsylvanian series. Critical areas were the belts of outcrop in and adjacent to the mountain uplifts in northern New Mexico; secondary, because of lack of information at the present time, were vast areas in which the Pennsylvanian strata are covered by representatives of later series and systems. Since much of New Mexico is structurally complex, it was clear that stratigraphy and structural geology must be considered together in mapping. This has provided much opportunity for examination of lateral stratigraphic variations that are often neglected in usual stratigraphic procedures.

The basis for a stratigraphic classification is either paleontologic or lithologic. Neither is completely independent, but clearly a decision must be reached early in such projects as the one presented here regarding which should be emphasized and what criteria should be employed to determine boundaries of units.

Stratigraphic classification based primarily on paleontologic criteria requires either much prior information on faunal sequences in the area under study and in other important areas of similar strata, or there must be time available for such study concurrent with the other phases of the stratigraphic work. Prior information on faunal sequences in the Pennsylvanian of New Mexico was not available; there was neither the time nor the facilities to undertake such work in conjunction with the assignment; and, finally, we were not impressed by the adequacy of such information in other areas with which comparison might be necessary. At the beginning of the work we were—and we still are—doubtful of the practical merits of mapping, or even the possibility of accurately identifying, the limits of faunal zones in series of the general type represented by the Pennsylvanian.

Development of a lithologic classification for the Pennsylvanian series in northern New Mexico is a complex problem. It requires decision as to procedure in defining major and minor divisions that directs attention to the evaluation of the importance of lithologic changes and disconformable relations. Even though lithologic character is the fundamental basis selected, it cannot be divorced from paleontology in problems of correlation, and therefore concurrent studies of the fossil content of the rocks must be undertaken.

Physical and theoretical evidence of disconformities and unconformities has been a major criterion whereby the Pennsylvanian series in other parts of the United States has been divided into its several units.[2] The use of such bases harks back to the opinion that diastrophic events of regional importance provide an adequate and very natural foundation for stratigraphic division. With such opinion we are in full accord, but we suspect that overuse of this method in the Pennsylvanian series has resulted in the development of a pseudo-uniform classification that does not agree with the observed variations throughout the North American continent.

It appears to us probable that many disconformities are local; that the physical evidence of disconformity, or of unconformity, in many instances is no measure of the time involved and affords no criterion whereby a major

[2] R. C. Moore and Others, "Correlations of Pennsylvanian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), pp. 657–705.

hiatus may be distinguished from a very minor, unimportant local break; and that paleontologists have often failed to discriminate between faunal change and faunal break. In consequence, we suspect that some disconformities and hiatuses have not been traced but have been postulated beyond the limits of their actual development.

We believe that sedimentation in many geosynclinal and foreland areas during Pennsylvanian time was nearly or quite continuous during periods of mountain-building marginal to such features. Observation in the field also leads to the conclusion that disconformities and unconformities in Pennsylvanian rocks in northern New Mexico most commonly exist on the margins of geanticlines, decrease in magnitude basinward, and, finally, are lost in continuous sequences of conformable strata in the basin areas.

Clearly, the measure of the magnitude of apparent hiatuses inferred from physical evidence is the degree of discontinuity of the biotas. Absence of biotas and not changes in assemblages due to processes of evolution, migration, or facies shift is evidence of a hiatus. To illustrate, the appearance of *Callipteris conferta* and some of its associates in strata of Permian(?) age is not a criterion of a hiatus between the lowest occurrence of such a flora and immediately subjacent rocks that contain the so-called *Odontopteris* flora. The organic succession is normal and characteristic of many sequences of late Paleozoic rocks. In alternations of marine and continental rocks the occurrence of primitive species of *Triticites* (*T. irregularis*, etc.) above advanced species of *Fusulina*, together with physical evidence, has been locally adjudged to indicate an important and very significant stratigraphic break or disconformity. If such is the case, there should clearly be a faunal break, demonstration of which requires the discovery of one or more intermediate or "mixed" faunas in areas where the break is spanned by passage beds.

The assumption that disconformities are widespread during periods of orogeny seems unjustified unless rather complete withdrawal of seas from the continental regions is clearly shown by a great array of data. Even then it is to be expected that sedimentation may have been continuous, but with shift from marine to continental facies, unless there was further elevation sufficient to develop coastal uplands rather than lowlands. On the basis of the local geology of northern New Mexico we suggest that orogeny in geanticlinal areas was accompanied, in some cases, by major and continuous sedimentation in flanking troughs, geosynclines, and forelands.

In northern New Mexico gradual lithologic changes that reflect widespread transgressions and regressions of marine embayments and the gradual development of geanticlines and their attending geosynclines are characteristic of the boundaries of units mapped in recent work. In belts marginal to geanticlines both disconformities and unconformities are common and are often of considerable magnitude, but it has not been demonstrated that these features extend into the more distal portions of the depositional areas.

Summarizing the above discussion, we have accepted lithologic features as a principal basis in dividing the Pennsylvanian series in northern New Mexico. Paleontology is considered a guide for recognition of formations and not a method of establishing them. The procedure has been followed of limiting units

by changes in sedimentation rather than by unconformities, which, in the area in question, have not been demonstrated to be regionally continuous or to represent important hiatuses. There has resulted from this procedure, which we believe to be in accord with important principles of sedimentation, the establishment of several contacts of stratigraphic units which are not "line-thin." Instead, the boundaries in many instances have been drawn in terms of transition zones.

NATURE OF SEDIMENTATION IN THE PENNSYLVANIAN SERIES

The Pennsylvanian and Permian(?) strata in northern New Mexico constitute a major sedimentary cycle. This cycle is characterized by two phases, one marine and the other continental.

The marine phase of sedimentation consists of (1) a suite of transgressive sediments; (2) evenly and widely distributed marine sediments that were deposited during a period of maximum marine transgression; and (3) unevenly distributed and restricted alternating marine and continental sediments that represent a period of offlap or marine regression. The strata that constitute this suite were deposited during those portions of the Pennsylvanian epoch locally characterized by development of geanticlines and sedimentation in geosynclines. Marine regression, at least to a minor extent, appears to have resulted from the rapid accumulation of clastic sediments, which appears to have exceeded subsidence in the geosynclines and in the foreland areas.

The continental phase of sedimentation has not been separated into minor units. It represents the final phase of geosynclinal sedimentation for the cycle and of geanticlinal maturity and old age.

MAJOR SUBDIVISIONS OF THE PENNSYLVANIAN SERIES IN NORTHERN NEW MEXICO

For the marine portion of the sedimentary cycle outlined above it is recommended that the term "Magdalena group" be used. Such usage is in rather close agreement with earlier definitions of the term.[3] The upper limit of the Magdalena group, as the term is used here, is not a time line but represents the limit of marine sedimentation in the area. The inferred final regression of the sea in any given area in northern New Mexico is undoubtedly a boundary of considerable importance.

For continental arkoses and red beds that rest conformably, disconformably, or unconformably on the Magdalena group over large areas, several terms have been used. Throughout much of the state "Abo formation" is accepted. In the Rowe-Mora Basin, where indivisible arkose and red shale range in age from Upper Pennsylvanian to Permian, "Sangre de Cristo formation" has been used. In the northern part of the Nacimiento Mountains the term "Cutler formation," which has been widely used in the adjacent San Juan Mountains, is applied to continental arkose.

MINOR SUBDIVISIONS OF THE PENNSYLVANIAN SERIES IN NORTHERN NEW MEXICO

Although it has been considered inadvisable to attempt subdivision of the Abo, Sangre de Cristo, or Cutler formations in this area, it is possible to separate the Magdalena group into several units of formational rank and member-rank. The separation has been based on lithologic changes that reflect transgres-

[3] C. H. Gordon, "Notes on the Pennsylvanian Formations in the Rio Grande Valley," *Jour. Geol.*, Vol. XV (1907), pp. 805–16.

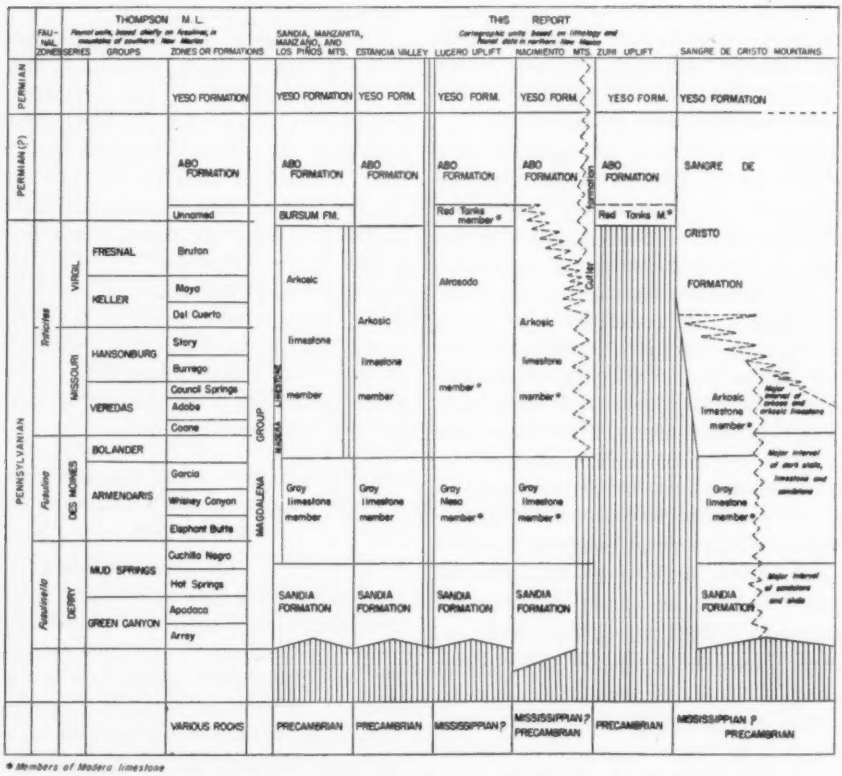
sions and regressions of the sea and periods of mountain-building.

Unconformities as unit boundaries have been taken into consideration in areas marginal to geanticlines, but such features do not provide sound criteria in the geosynclines. Faunal zones have been considered a local guide to formations and members.

The subdivision of the Magdalena group, according to the foregoing principles, is rather simple, for this group contains stratigraphic units thicker than in other Pennsylvanian formations and makes possible the recognition of formations and members as local units (Fig. 1).

The basal unit of the Magdalena group is the Sandia formation,[4] a dominantly clastic deposit of early Pennsylvanian age. Since it is a transgressive suite of sediments, it is evident that the unit must, in a regional sense, vary slightly in age limits. Such variation is minor, according to available data. Locally the basal sediments of the Sandia

[4] C. L. Herrick, "The Geology of the White Sands of New Mexico," *Jour. Geol.*, Vol. VIII (1900), pp. 112–18.



CURRENT NOMENCLATURE AND CORRELATION OF PENNSYLVANIAN ROCK UNITS IN PARTS OF NEW MEXICO

FIG. 1

formation have been dated by contained fossils as of upper Morrow age.[5] The upper limits of the formation appear to lie within the *Fusulinella* zone and, in consequence, fall within what has been called the "Lampasas series" by some geologists in the mid-continent region.

The remainder of the Magdalena group, represented by dominantly marine sediments, is, in most of northern New Mexico, assigned to a single formation, the Madera limestone, which has been divided into several local members. Justification for this separation into members rather than into formations is found in the major difficulties of closely delimiting units that show gradual transition at their contacts. In the Lucero Uplift, on the margin of the Colorado plateaus, the Gray Mesa, Atrasado, and Red Tanks members of the Madera limestone have been recognized.[6] In the ranges east of the Rio Grande the Madera limestone[7] has been divided into a lower gray limestone member and an upper arkosic limestone member, and the Bursum formation has been locally mapped at the top.[8] This nomenclature has likewise been used in the Sierra Nacimiento[9] and in the southern quadrangles of the Sangre de Cristo Mountains.[10]

Farther north, in the Sangre de Cristo Mountains, equivalents of the Sandia and Madera formations show major changes in lithology and marked thickening. Since this area is now being mapped, it is not advisable to recommend a final nomenclature.

POSITION OF GEANTICLINES, GEOSYNCLINES, AND FORELANDS

It now seems desirable to consider the general distribution of major positive areas and depositional basins that characterized the region during much of Pennsylvanian time (Fig. 2). Two large geanticlines or linear positive elements manifested themselves as major features in New Mexico and greatly influenced sedimentation over large areas. The easternmost of these is the Sierra Grande arch, which enters the state from the northeast in Union County and extends southwestward for an unknown distance. The second is the Uncompahgre positive axis, which enters the state from the northwest in Rio Arriba and Taos counties, has an arcuate form, and extends at least into central Torrance County. Of less regional importance but locally influencing sedimentation to a marked degree is the Pedernal axis in western Torrance and southwestern San Miguel counties. The Peñasco or Nacimiento–San Pedro positive axis and its linear or echelon continuation, the Joyita axis, are likewise pronounced but of secondary regional importance.

[5] S. A. Northrop and G. H. Wood, "Geology of the Nacimiento and San Pedro Mountains and Adjacent Plateaus," *U.S. Dept. Int., Geol. Surv., Oil and Gas Investigation, Prelim. Map 57* (1946).

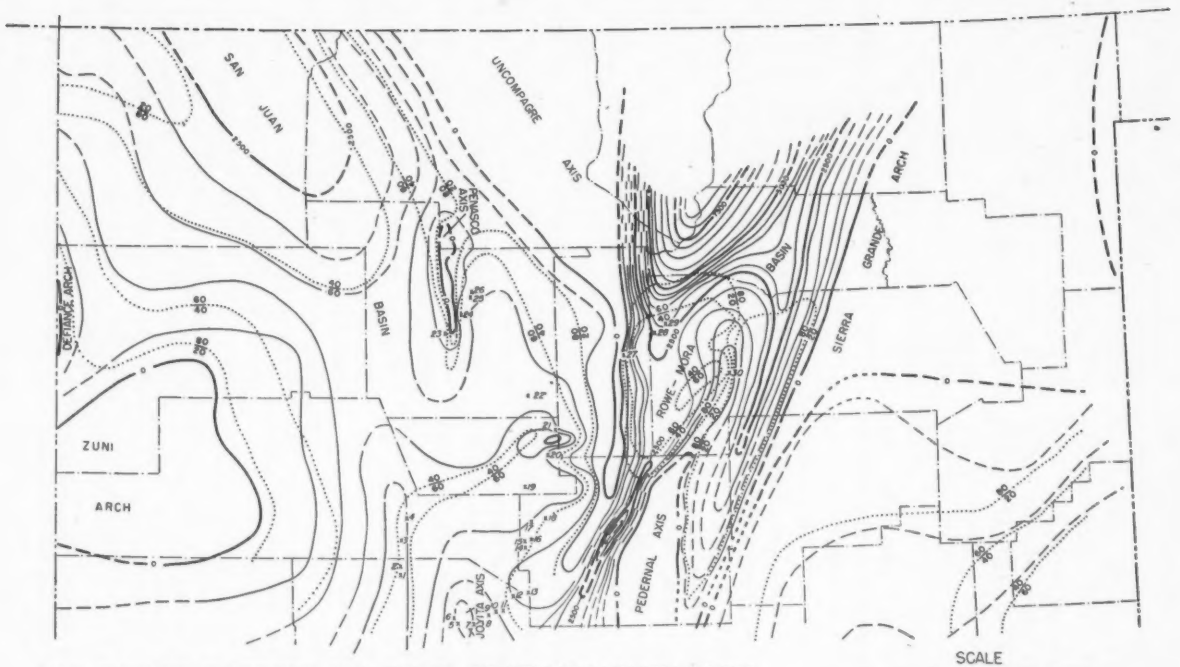
[6] V. C. Kelley and G. H. Wood, "Lucero Uplift, Valencia, Socorro, and Bernalillo Counties, New Mexico," *U.S. Dept. Int., Geol. Surv., Oil and Gas Investigation, Prelim. Map 47* (1946).

[7] C. B. Read and Others, "Geologic Map and Stratigraphic Sections of Permian and Pennsylvanian Rocks in Parts of San Miguel, Sante Fe, Sandoval, Bernalillo, Torrance, and Valencia Counties, North Central New Mexico," *U.S. Dept. Int., Geol. Surv., Oil and Gas Investigation, Prelim. Map 21* (1944).

[8] R. H. Wilpolt, A. J. MacAlpin, R. L. Bates, and Georges Vorbes, "Geologic Map and Stratigraphic Sections of Paleozoic Rocks of Joyita Hills, Los Piños Mountains, and Northern Chupadera Mesa, Valencia, Torrance, and Socorro Counties, New Mexico," *U.S. Dept. Int., Geol. Surv., Oil and Gas Investigation, Prelim. Map 61* (1946).

[9] Northrop and Wood, ftn. 5.

[10] S. A. Northrop and Others, "Geologic Maps of the Las Vegas Basin and of the Foothills of the Sangre de Cristo Mountains, San Miguel and Mora Counties, New Mexico," *U.S. Dept. Int., Geol. Surv.* (in preparation).


SAN JUAN BASIN
UNCOMPAGRE AXIS
PENASCO AXIS
DEFIANCE ARCH
ZUNI ARCH
ROWE-MORA BASIN
PEDERNAL AXIS
SIERRA GRANDE ARCH
SCALE
10 0 10 20 30 40 MILES
Lines of equal thickness drawn at intervals of 500 feet.
Ratio of clastic to calcareous sediments. Upper number is clastic factor, lower is calcareous factor.
Number and location of graphic section.

MAP SHOWING THICKNESS AND FACIES OF PENNSYLVANIAN ROCKS IN PARTS OF NORTHERN NEW MEXICO

FIG. 2

The inactive arches of the Zuni and Defiance areas are near the New Mexico–Arizona state boundary. Although these features influenced distribution of Pennsylvanian sediments, they were not major contributors of clastic materials.

The major geosyncline, which has been called the "Rowe-Mora Basin" or "trough," lies between the Sierra Grande and the Uncompahgre geanticlines. Between the Uncompahgre axis and the Peñasco-Joyita axis lies a minor basin, and farther west is the ancestral or Pennsylvanian San Juan Basin, which appears to have been in part geosynclinal and in part foreland.

In addition to indicating in a general fashion the positions of geanticlines, basins, and forelands, Figure 2 shows approximate thicknesses of Pennsylvanian sediments in northern New Mexico on the basis of present available data. Since the Pennsylvanian strata of this area are dominantly of two types, clastic or calcareous, it is apparent that some expression of facies can be achieved by contouring the ratio of clastic to calcareous sediments in measured sections. By this means a quantitative expression of certain facies distribution is established.

In the San Juan Basin of western New Mexico both thicknesses and facies of the Pennsylvanian rocks are shown in a tentative fashion, with the recognition that additional data from drilling will result in revision. On the flanks of the Zuni and Defiance uplifts data are available, and in north-central New Mexico numerous belts of outcrops in and around the various mountain ranges provide much information. East of the Sangre de Cristo Mountains front, data are inadequate for other than very tentative plotting of thickness and facies lines.

Of interest in Figure 2 are gradual shifts from calcareous to dominantly clastic facies in the Rowe-Mora Basin in passing from the southern bifurcation to the broad northern portion. This major facies shift is accompanied by a marked expansion of the Lower Pennsylvanian interval. Complex facies and thickness relations of Pennsylvanian strata are, in fact, apparent throughout the entire ancestral Rocky Mountain province. To the southwest and to the west there are suggested, on the basis of widely spaced data, more gradual changes in thickness and facies. In the San Juan Basin the location of the deeper portion of the late Paleozic Basin adjacent to the Uncompahgre geanticline is evident."

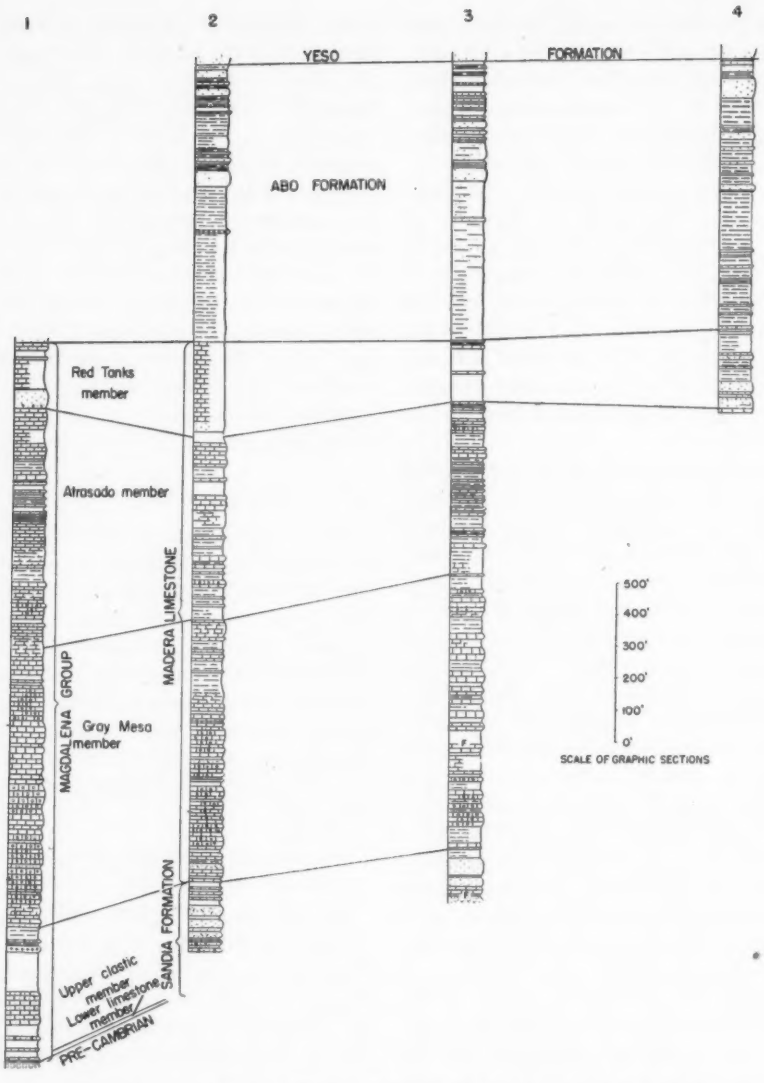
STRATIGRAPHIC SECTIONS

The following group of sections illustrates some of the lithologic variations in the Pennsylvanian series of northern New Mexico. For more detailed data the reader is referred to reports and maps cited above. The purpose of these graphic sections is to give general impressions of typical sequences, and a sufficient number of groups shows the numerous details of correlation to be beyond the scope of this paper.

LUCERO UPLIFT, VALENCIA, SOCORRO, AND BERNALILLO COUNTIES, NEW MEXICO

In the Lucero Uplift, which locally constitutes the margin of the Colorado Plateaus, approximately 2,300 feet of Pennsylvanian sediments, constituting the Magdalena group, are exposed (see Fig. 3). The basal portion of the sequence

" Although the clastic-calcareous ratio along the Zuni and Defiance uplift is sufficiently high to suggest that the axial portions of these features may have been major sources of clastic sediments, it should be realized that in such areas only uppermost Pennsylvanian strata are known at or near outcrop belts. In contrast, in the ancestral Rocky Mountain area, far larger fractions of Pennsylvanian time are represented by sediments adjacent to the margins of basins.



GRAPHIC SECTIONS OF PALEOZOIC STRATA FROM NAVAJO GAP TO CARRIZO ARROYO

Numbers of sections are those of localities in list

HORIZONTAL SCALE

0 1 2 3 4 5 6 MILES

FIG. 3

is the Sandia formation, which contains *Fusulinella* spp., and rests on problematical Mississippian strata[12] or directly on pre-Cambrian granite.

Overlying the Sandia formation is the Madera limestone, which has been divided into three local members. The oldest of these is the Gray Mesa member, which consists of an almost continuous sequence of dark-gray limestone containing microfaunas at its base, characterized by the genus *Fusulinella*. A sequence of faunas higher in the member is notable in that it includes a rather complete series of forms of the genus *Fusulina*. Evidently on the basis of microfaunas these latter strata constitute the major portion of the Des Moines group, although the basal portion is possibly of Lampasas age.

Resting conformably on the Gray Mesa member of the Madera limestone is the Atrasado member, an alternation of limestone; gray, olive, and red shale; and arkosic sandstone. At its base a small fauna, including advanced types of *Fusulina* spp. and also *Prismopora* sp., has been identified. Less than 20 feet higher and in the same sequence of thin alternating limestones and gray shale, species of *Triticites* belonging to the *irregularis* group have been identified. Higher still is encountered the standard sequence of species of *Triticites* that are characteristic of Pennsylvanian successions in New Mexico. The zone of *T. ventricosus* and associated forms occurs in the upper part, and therefore the higher beds of this member are considered to be generally equivalent to the Virgil group of the Mid-Continent region.

The youngest strata of the Madera limestone have been separated as a third unit, the Red Tanks member. This consists of red shale and sandstone, capped by one or more ledges of gray limestone containing an abundance of *T. ventricosus*. It may be of Upper Virgil age; but, because of the occurrence of a similar unit a short distance to the southeast containing occasional *Schwagerina* sp. associated with a similar abundance of *T. ventricosus*, the Red Tanks member possibly may be of Permian(?) age.

The Abo formation of Permian(?) age succeeds the Red Tanks member of the Madera limestone with apparent conformity. The nature of the sequence in the upper part of the Madera suggests a gradual transition from marine to continental strata, and no important hiatus appears to separate the Abo from the Madera limestone in this area.

[12] Limestone locally present at the base of the section may be Lake Valley in age. Neither lithologic character nor fossil content supports the correlation sufficiently to permit an unqualified statement.

LA JOYA, LOS PIÑOS MOUNTAINS, AND NORTHERN CHUPADERA MESA, SOCORRO AND VALENCIA COUNTIES, NEW MEXICO

The Pennsylvanian strata in this area are included in the Magdalena group and consist of gray cherty limestone, sandstone, shale, and minor amounts of conglomerate (see Fig. 4). These rocks rest with angular unconformity or disconformity on various pre-Cambrian metamorphic and igneous rocks.

The Sandia formation includes gray sandstone, quartz conglomerate, shale, and minor quantities of gray arenaceous limestone. It contains numerous fossils of Lower Pennsylvanian age, including several species of *Fusulinella*.

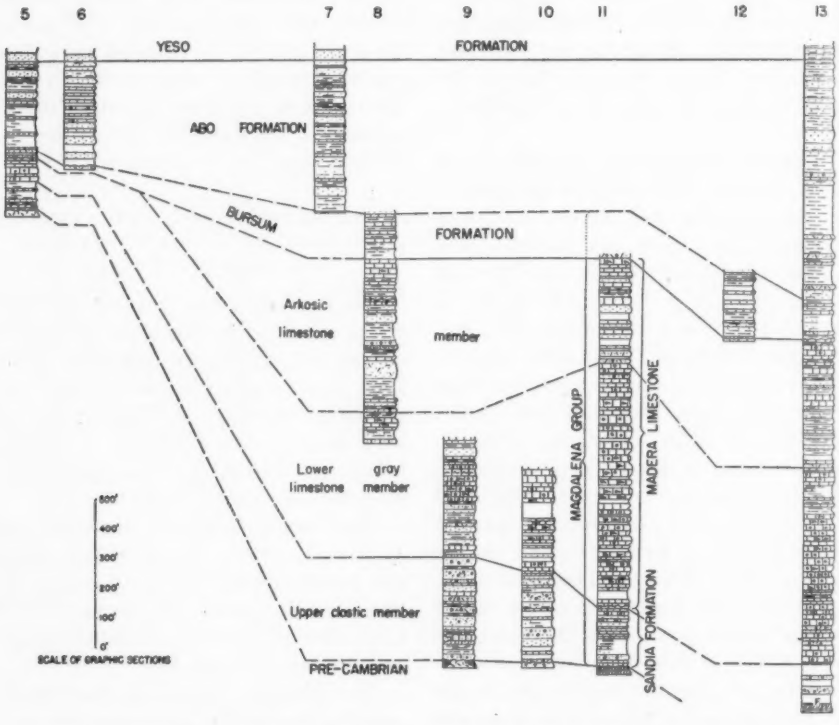
The Madera limestone conformably overlies the Sandia formation and consists of a lower gray limestone member and an upper arkosic limestone member. These units are approximately equivalent to the Gray Mesa and Atrasado members in the Lucero Uplift. However,

it is not clear whether the Red Tanks member of the Madera limestone in the Lucero Uplift area is correlative with the upper part of the arkosic limestone member or with the succeeding Bursum formation.

The lower gray limestone member contains massive or thin-bedded cherty limestone interbedded with minor amounts of shale and forms a great cliff in many places.

In contrast, the arkosic limestone member consists of medium- or thin-bedded limestone interbedded with gray, black, and red shale, sandstone, and arkosic sandstone. Conglomerate is usually present. The lower portion of the member is a slope-forming, dominantly clastic unit, whereas the upper portion is usually a cliff-forming sequence of limestone ledges.

Overlying the arkosic limestone member of the Madera limestone in the typical succession is the arkosic and calcareous Bursum formation of Permian(?) age. The latter is succeeded by the Abo formation, which, in this area, consists of arkosic and quartzitic clastic material.



GRAPHIC SECTIONS OF PALEOZOIC STRATA IN LA JOYA, LOS PIÑOS MOUNTAINS, AND CHUPADERA MESA AREAS

Numbers of sections are those of localities in list.

HORIZONTAL SCALE 0 1 2 3 4 MILES

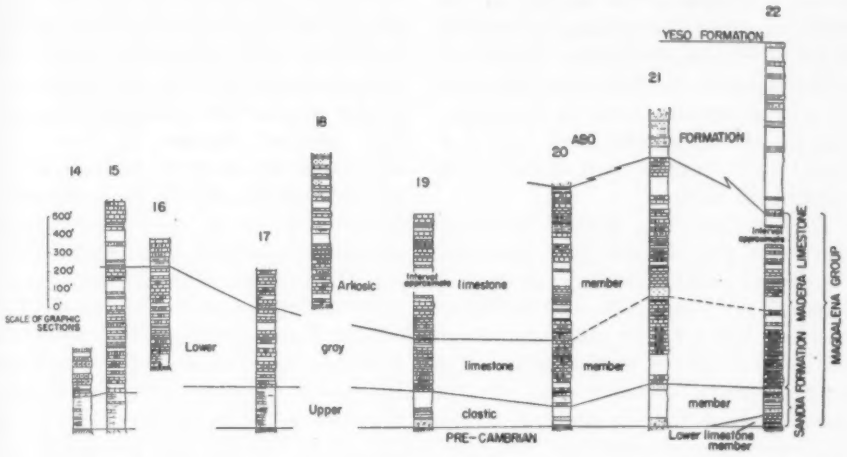
FIG. 4

The lower gray limestone member of the Madera contains marine fossils, including a suite of species of *Fusulina*, indicating a dominantly Des Moines age for the unit. Species of *Fusulinella* occur in abundance, however, in the basal beds of this unit at some localities. In the arkosic limestone member of the Madera, species of *Triticites* are found a short distance above the base of the unit, and a rather complete sequence of forms is known to be present. The Bursum formation contains *Schwagerina* sp. in association with abundant *T. ventricosus*. The thinning of the Magdalena group in the vicinity of the Joyita Hills is of interest. In this area the arkosic limestone member of the Madera is absent, owing to nondeposition on the Joyita axis, a positive feature that appeared during Upper Pennsylvanian time.

RED CANYON, MANZANO MOUNTAINS, TO GALLEGOS RANCH, SANDIA MOUNTAINS

The group of sections shown in Figure 5 extends from Red Canyon, near the southern end of the Manzano Mountains, northward along the eastern slope of the Manzano, Manzanita, and Sandia ranges to Gallegos Ranch, near the northern termination of the Sandia Mountains. As in the other groups of the section, Pennsylvanian marine strata are assigned to the Magdalena group.

A massive limestone associated with basal clastics occurs in the northern part of the Sandia Mountains below the Sandia formation. It was originally assigned to the Pennsylvanian, but, because it contains no diagnostic fossils and on the basis of recent work in other portions of the state, it is considered by us



GRAPHIC SECTIONS OF MAGDALENA GROUP AND ABO FORMATION IN MANZANO, MANZANITA, AND SANDIA MOUNTAINS

Numbers of sections are those of localities in list.

FIG. 5

to be a possible equivalent of the Leadville limestone, of Mississippian age.

Resting with pronounced disconformity on this limestone of supposed Mississippian age, or directly on the pre-Cambrian granite and metamorphic rocks of the Sandia and Manzano mountains, is the Sandia formation. This unit shows much variation in detail in the several sections illustrated but maintains the rather constant characteristic of alternations of irregularly bedded sandstone, thin coal seams, carbonaceous shale, and occasional impure beds of limestone. Species of *Fusulinella* have been collected from the upper part of the unit in most of the sections.

In the succeeding Madera limestone the lower part of the gray limestone member also carries faunas characterized by species of *Fusulinella*, and the higher parts contain a rather full succession of the several species of this genus. The most advanced species extend into the basal part of the superjacent arkosic limestone member and are there succeeded by a series of species of *Triticites* that culminates in *T. ventricosus*.

Clearly, there is much variation in detail in this group of sections but little variation in general character. There is no physical evidence of any major hiatus in the sequence, which is considered a thin, but rather continuous, representation of marine deposition in a foreland area.

The Abo formation of Permian(?) age overlies the Madera formation with apparent conformity. At most places the contact suggests gradational or transitional relationships.

PEÑASCO ARROYO TO JEMEZ SPRINGS, NACIMIENTO MOUNTAINS, SANDOVAL COUNTY, NEW MEXICO

Guadalupe Box is in the middle of the Rio de las Vacas drainage basin in the heart of the Nacimiento Mountains and offers the only complete and structurally simple section in the range. In the canyon of the Vacas, Pennsylvanian strata rest on a thin representative of the limestone member of the Sandia formation that the writers regard, on lithologic grounds, as a possible equivalent of the Leadville limestone (see Fig. 6).

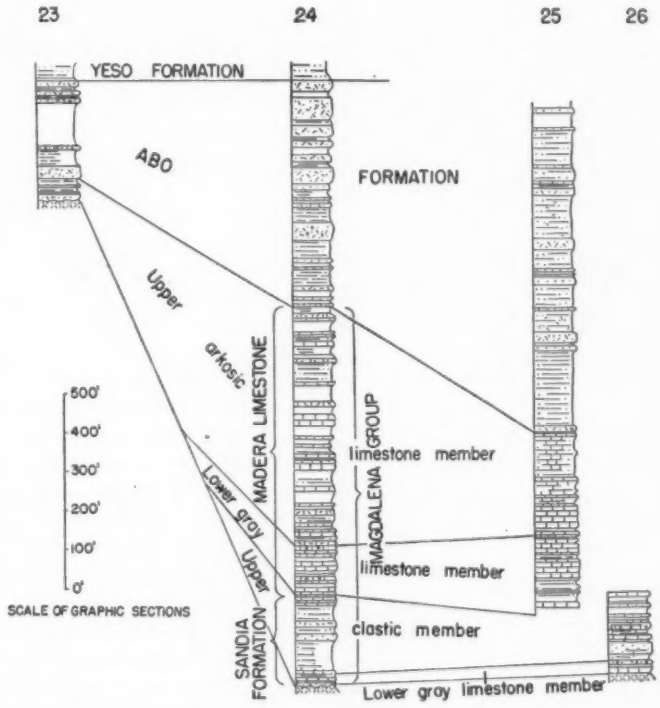
Disconformably overlying this limestone is the upper member of the Sandia formation, which consists of clastic beds and thin limestones. From the basal beds of this member the following fauna has been collected: *Aulopora* sp. cf. *A. prosseri*, *Composita* sp. cf. *C. gibbosa*, *Derbya* sp., *Dictyoclostus* sp. cf. *D. hermosanus*, *Hustedia* sp. cf. *H. miseri*, *Schizophora oklahomae*, *Spirifer occidentalis*. This fauna is believed to be of Morrow age. From the higher parts of the Sandia formation here and at near-by localities, *Millerella* sp., *Prismopora* sp., and *Fusulinella* sp. have been identified. Clearly this part of the Sandia formation in the area is of Morrow and Lampasas age.

In the overlying Madera limestone the lower gray limestone member, which rests conformably on the Sandia formation, has yielded the following fossils: *Chonetina?* sp., *Derbyia crassa*, *Linoproductus* sp. *aff. L. platyumbonus*, *Marginifera* sp. cf. *M. missouriensis*, *Spirifer occidentalis*, *S. rockymontanus*, *Fusulina* spp., *Wedekindelina* sp., *Fusulinella* sp. This fauna indicates that the containing beds are of late Lampasas and of early and middle Des Moines age. We do not recognize, at this time, any hiatuses within the sequence.

The succeeding arkosic limestone member of the Madera contains, immediately above the contact with the lower gray limestone, abundant *Chaetetes milleporaceous;* and 60 feet above the base the following fauna has been found: *Composita trilobata*, *Dictyoclostus colora-*

doensis, Dielasma bovidens, Linoproductus platyumbonus, Neospirifer triplicatus, Phricodothyris perplexa, Punctospirifer kentuckyensis, Acanthopecten carboniferus, Solenomya? sp. Approximately 280 feet above the base of the member the following forms have been collected: *Neospirifer triplicatus, Allorisma terminale, Edmondia* sp., *Pseudomonotis equistriata, Bellerophon* sp. cf. *B. giganteus, Straparollus* (*Euomphalus?*) sp. Near the top of the member, *N. triplicatus, Marginifera wabashensis, A. terminale,* and *T. ventricosus* have been found. This sequence is rather typical of the lithologic and faunal succession in the upper member of the Madera limestone. There appear to be no important disconformities, and probably the sequence represents slow but nearly continuous sedimentation.

The group of sections in Figure 6 shows interesting variations in passing westward to Peñasco Arroyo. Clearly, the Sandia formation and the lower member of the Madera limestone dis-



GRAPHIC SECTIONS OF PALEOZOIC STRATA FROM PENASCO ARROYO TO JEMEZ SPRINGS, NEW MEXICO

Numbers of sections are those of localities in list.

HORIZONTAL SCALE

0 1 2 3 4 5 6 MILES

FIG. 6

appear, and the upper arkosic limestone member of the Madera thins. The absence of the lower part of the Magdalena group may be explained by overlap, and the thinning of the upper unit of the group probably resulted from the rise of a strong, positive element during late Pennsylvanian time.

LAMY TO BERNAL, SANGRE DE CRISTO MOUNTAINS, SANTE FE AND SAN MIGUEL COUNTIES, NEW MEXICO

Along Pecos Valley in the southernmost part of the Sangre de Cristo Mountains, Pennsylvanian strata referred to the Magdalena group are well exposed (see Fig. 7).

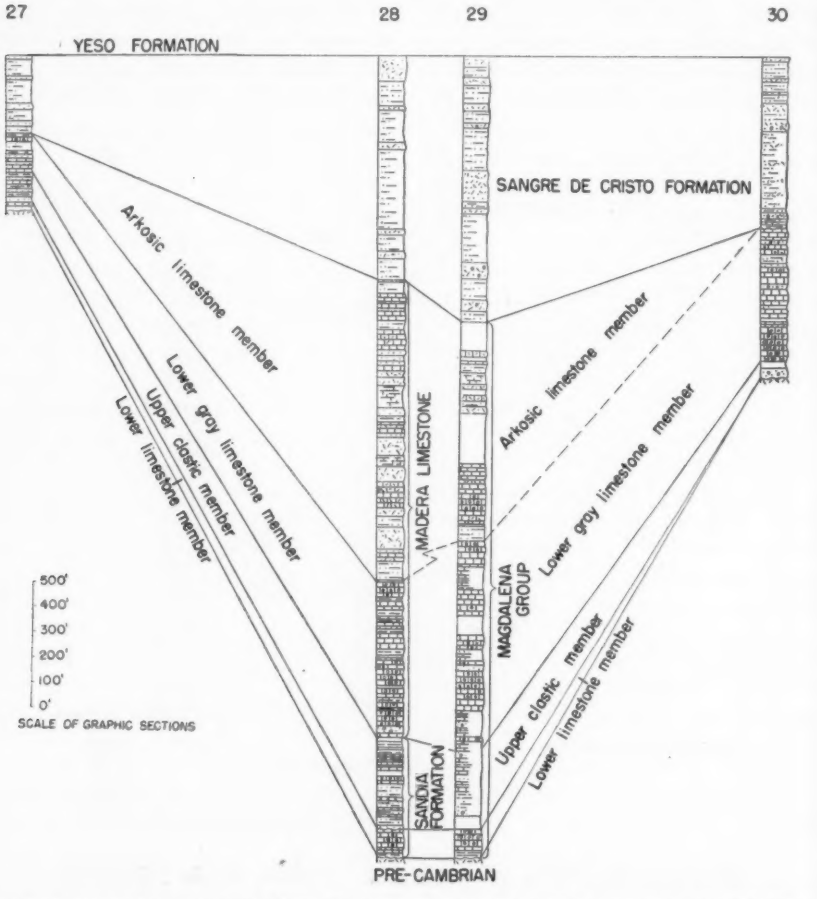


FIG. 7

Resting on the pre-Cambrian or on a regolith, massive limestone has been classified tentatively as the lower member of the Sandia formation. This limestone may be, however, of Mississippian age or older, but it has yielded no diagnostic fossils. Overlying it is the upper, or clastic, member of the Sandia formation, which consists of shale, sandstone, impure limestone, and thin coal. Both the invertebrate and the fossil plants of these beds suggest correlation with strata of Lampasas age elsewhere.

The Madera limestone, which conformably succeeds the Sandia formation, consists of a lower, gray limestone member and an upper, arkosic limestone member. The lower member is dominantly limestone, with minor alternations of calcareous shale and small quantities of sandstone. It contains, in its lower portion, several species of *Fusulinella* and in its upper portion species of *Fusulina*. Probably this member is chiefly of Des Moines age, although possibly the lowermost strata are of Lampasas age.

Overlying the lower gray limestone member of the Madera limestone, and at many points transitional with it, are alternations of limestone, sandy and arkosic limestone, arkose, and red, olive, and gray shale that constitute the arkosic limestone member. In the lowest beds of this unit, fossils of Upper Des Moines age have been collected. Numerous invertebrates in the succeeding portions of the member suggest, however, an Upper Pennsylvanian age assignment, as do also fossil plants collected in its middle and upper parts.

The Sangre de Cristo formation, a highly variable succession of arkosic and red beds, conformably or unconformably overlies the Magdalena group. Possibly the lower portion of this unit is, at some localities, Pennsylvanian in age. The middle and upper parts have been dated, on the basis of fossil plants, as Permian(?).

Both east and west of Pecos Valley the Pennsylvanian rocks thin, because of the development of late Pennsylvanian positive elements. At Lamy, New Mexico, a thin sequence of the Sandia formation and the lower member of the Madera are overlain by arkose of the Sangre de Cristo formation. A similar occurrence is apparent in the vicinity of Bernal.

LIST OF LOCALITIES OF GRAPHIC SECTIONS

1. Ladron Mountains: sections 9, 10, 14, 15, and 23, T. 3 N., R. 3 W., Socorro County, New Mexico.
2. Monte de Belen: sections 13, 14, 23, 24, and 32, T. 4 N., R. 3 W., Socorro County, New Mexico.
3. Gray Mesa: section 13, T. 5 N., R. 3 W., and section 25, T. 6 N., R. 3 W., Socorro County, New Mexico.
4. Carrizo Arroyo: section 7, T. 6 N., R. 2 W., and section 1, T. 6 N., R. 3 W., Valencia County, New Mexico.
5. Central part of Joyita Hills, Sevilleta Grant, Socorro County, New Mexico.
6. Northern part of Joyita Hills, Sevilleta Grant, Socorro County, New Mexico.
7. Headwaters of Arroyo Cibola, southern Los Piños Mountains, Sevilleta Grant, Socorro County, New Mexico.
8. Head of Arroyo Cibola, Los Piños Mountains, Sevilleta Grant, Socorro County, New Mexico.
9. South-central part of Los Piños Mountains, Sevilleta Grant, Socorro County, New Mexico.
10. Central part of Los Piños Mountains, Sevilleta Grant, Socorro County, New Mexico.
11. East-central part of Los Piños Mountains, Sevilleta Grant, Socorro County, New Mexico.
12. Montosa Arroyo: sections 13 and 14, T. 2 N., R. 4 E., Socorro County, New Mexico.
13. Abo Canyon: southeastern part of Casa Colorado Grant, and portions of T. 2 and 3 N., R. 5 and 6 E., between Sais Quarry

and Abo State Monument, Socorro and Torrance Counties, New Mexico.

14. Red Canyon: section 28, T. 5 N., R. 5 E., Torrance County, New Mexico.
15. Arroyo de los Piños Reales: section 21, T. 5 N., R. 5 E., Torrance County, New Mexico.
16. New Canyon: sections 10 and 11, T. 5 N., R. 5 E., Torrance County, New Mexico.
17. Burro Mountain: section 14, T. 6 N., R. 5 E., Torrance County, New Mexico.
18. Tajique Arroyo: west of Tajique, Torrance County, New Mexico.
19. Hell Canyon: sections 21 and 22, T. 8 N., R. 5 E., Bernalillo County, New Mexico.
20. Cedro Canyon: sections 26 and 35, T. 10 N., R. 5 E., Bernalillo County, New Mexico.
21. San Antonito vicinity: section 22, T. 11 N., R. 6 E., Bernalillo County, New Mexico.
22. Gallegos Ranch: 1½ miles east of Placitas, Sandoval County, New Mexico.
23. Peñasco Arroyo: sections 20 and 21, T. 16 N., R. 1 E., Sandoval County, New Mexico.
24. Guadalupe Box: Cañon de San Diego Grant, Sandoval County, New Mexico.
25. Jemez Springs: Cañon de San Diego Grant, Sandoval County, New Mexico.
26. Soda Dam: Cañon de San Diego Grant, Sandoval County, New Mexico.
27. Vicinity of Apache Canyon, near Lamy, Santa Fe County, New Mexico.
28. Pecos River: section 33, T. 17 N., R. 12 E.; and sections 4, 9, 16, and 20, T. 16 N., R. 12 E., and in the Pecos Grant, San Miguel County, New Mexico.
29. Vallecitos: vicinity of Cow Creek, sections 7 and 18, T. 16 N., R. 13 E., San Miguel County, New Mexico.
30. Bernal Creek, four miles north of Bernal, San Miguel County, New Mexico.

REGIONAL VARIATIONS IN PENNSYLVANIAN LITHOLOGY

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ABSTRACT

Recurring similar sequences of strata characterize the Pennsylvanian in most regions in the United States. The Illinois type of sequence has been called the "cyclothem" and the Kansas type the "megacyclothem." There are many variations in the pattern of these rhythmic successions, and within the Pennsylvanian areas of the United States they include representatives of nearly all kinds of sedimentary rocks. Thirty-six representative Pennsylvanian successions, two from the Mississippian, and one from the Lower Permian are graphically represented. The rhythmic successions may record diastrophic or climatic fluctuations of continent-wide extent, and the varied type of successions composing them may result from locally variable features of environment, topography, climate, or the configuration of land and sea.

Data sheets to record quantitative lithologic variations in the Pennsylvanian and its principal subdivisions have been devised. From these sheets, prepared on the basis of one for each county, various types of lithologic-variation maps and isopach maps can be prepared.

INTRODUCTION

The arrangement of Pennsylvanian strata of varied lithology into an orderly sequence several times repeated was first described by J. A. Udden from the Peoria quadrangle, Illinois.[1] The more widespread occurrence of such a rhythmic pattern was reported by J. M. Weller.[2] He stated that in western Illinois the succession consists ideally of ten beds, named as follows in ascending order: (*a*) sandstone, (*b*) sandy and micaceous shale, (*c*) "fresh-water" limestone, (*d*) underclay, (*e*) coal, (*f*) gray nonmarine shale, (*g*) marine limestone, (*h*) black slaty shale, (*i*) marine limestone and calcareous shale, and (*j*) shale containing ironstone bands or nodules in the upper part and thin limestone layers in the lower part. Each succession is locally separated from underlying and overlying successions by an erosional unconformity. To this frequently repeated rhythmic succession the name "cyclothem" was applied.[3] A symposium held at Urbana in 1930 brought out the fact that successions of cyclic or rhythmic character were to be found in Ohio,[4] West Virginia,[5] and the northern and southern mid-continent areas,[6] as well as in Illinois; but the details of the rhythmic succession in each of these areas are unlike those of Weller's western Illinois cyclothem. The plane of separation between cyclothems was placed by Weller at the base of the sandstone member (*a*), but Stout prefers the base of the coal (*e*), Reger the top of the sandstone (*a*), and Moore the top of the upper marine limestone (*i*) as more convenient planes of separation in their

[1] "Geology and Mineral Resources of the Peoria Quadrangle," *U.S. Geol. Surv. Bull. 506* (1912), pp. 27, 47–50.

[2] "Cyclical Sedimentation of the Pennsylvanian Period and Its Significance," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 97–135; "The Conception of Cyclical Sedimentation during the Pennsylvanian Period," *Ill. Geol. Surv. Bull. 60* (1931), pp. 163–77.

[3] H. R. Wanless and J. M. Weller, "Correlation and Extent of Pennsylvanian Cyclothems," *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), p. 1003.

[4] Wilber Stout, "Pennsylvanian Cycles in Ohio," *Ill. Geol. Surv. Bull. 60* (1931), pp. 195–216.

[5] David B. Reger, "Pennsylvanian Cycles in West Virginia," *Ill. Geol. Surv. Bull. 60* (1931), pp. 217–39.

[6] Raymond C. Moore, "Pennsylvanian Cycles in the Northern Mid-continent Region," *Ill. Geol. Surv. Bull. 60* (1931), pp. 247–57; Frederick B. Plummer, "Pennsylvanian Sedimentation in Texas," *Ill. Geol. Surv. Bull. 60* (1931), pp. 259–69.

respective areas if the cyclothem is to be considered primarily a formational unit to be used in geologic mapping. Later, Moore described a megacycle or cycle of cycles from the Kansas section,[7] recording four or five rather than one, marine invasion, but with a different sedimentary record for each until the corresponding cycle of the next megacycle has been reached (Fig. 3, col. 4). A form of cyclic sedimentation in the Rocky Mountains has been described[8] and one each from Michigan,[9] England,[10] the Silesian Basin,[11] and the Donetz Basin.[12] During the summer of 1934 the author spent a few weeks studying the Pennsylvanian succession in various parts of Colorado, New Mexico, Wyoming, South Dakota, and Utah. He found that at virtually every place the succession of rock types exhibits some form of rhythmic pattern but that the rock sequence recording the rhythm varies greatly from place to place and nowhere greatly resembles Weller's western Illinois cycle, Stout's Ohio cycle, or Moore's Kansas megacycle. The Rocky Mountain successions differ from those farther east in that they contain very little carbonaceous sediment (coal or black shale) and comparatively little argillaceous sediment (shale and underclay) and in that the sandstones are more generally arkosic than in areas farther east. The sequence composing the rhythmic alternation is generally simpler, being composed of two or three rock types rather than eight or ten, as in the areas farther east. These western successions are reported to be much less widespread than those farther east,[13] and they may not record comparable periods of time. Since 1934, opportunity has been afforded the author to study the Pennsylvanian successions in Indiana, Ohio, Kentucky, Pennsylvania, West Virginia, Virginia, Tennessee, and Georgia during 1937–39 and Wyoming during 1945; and brief field excursions to Pennsylvanian areas in Alabama, Iowa, Missouri, Oklahoma, Texas, and New Mexico have provided additional illustrations of variation in cyclic successions.

In this paper it is proposed to present some of the varied types of succession from the Pennsylvanian of the United States that may be considered cyclic. There are also shown two columns (Fig. 2, col. 8, and Fig. 4, col. 1) illustrating cyclic successions from the later Mississippian (Chester and Brazer) and one (Fig. 3, col. 9) from the Early Permian (Big Blue), showing that types of rhythmic successions are to be found in systems adjoining the Pennsylvanian. The suggestion is made that the various sequences are somewhat comparable in the time required for their deposition and that they result from changes in sea-level, changes in climate, and diastrophic disturbances not entirely local to the

[7] "Stratigraphic Classification of the Pennsylvanian Rock of Kansas," *Kan. Univ. Bull. 22* (1935), pp. 29–35.

[8] J. Harlan Johnson, "Contribution to the Geology of the Sangre de Cristo Mountains of Colorado," *Proc. Colo. Sci. Soc.*, Vol. XII (1929), pp. 1–11.

[9] W. A. Kelly, "Pennsylvanian Stratigraphy near Grand Ledge, Michigan," *Jour. Geol.*, Vol. XLI (1933), pp. 79–86.

[10] R. G. Hudson, "On the Rhythmic Succession of the Yoredale Series in Wensleydale," *Proc. Yorkshire Geol. Soc.*, Vol. XX, Part I (1923–24), pp. 1–11; James Brough, "On Rhythmic Deposition in the Yoredale Series," *Proc. Univ. Durham Philos. Soc.*, Vol. VIII, Part II (1929), pp. 116–25.

[11] Axel Born, "Periodizität epirogener Krustenbewegungen," *Rept. 16th Internat. Geol. Cong., 1933*, Vol. I (1936), p. 172.

[12] B. Tschernyschew, "Carbonicola, Anthracomya, and Naiadites of the Donetz Basin," *Trans. Geol. and Prospect. Serv., U.S.S.R.*, Fasc. 72 (1931), pp. 109–11; A. W. Grabau, "The Permian of Mongolia," *Amer. Mus. Nat. Hist., Natural History of Central Asia*, Vol. IV (1931), pp. 432–42.

[13] C. B. Read, personal communication.

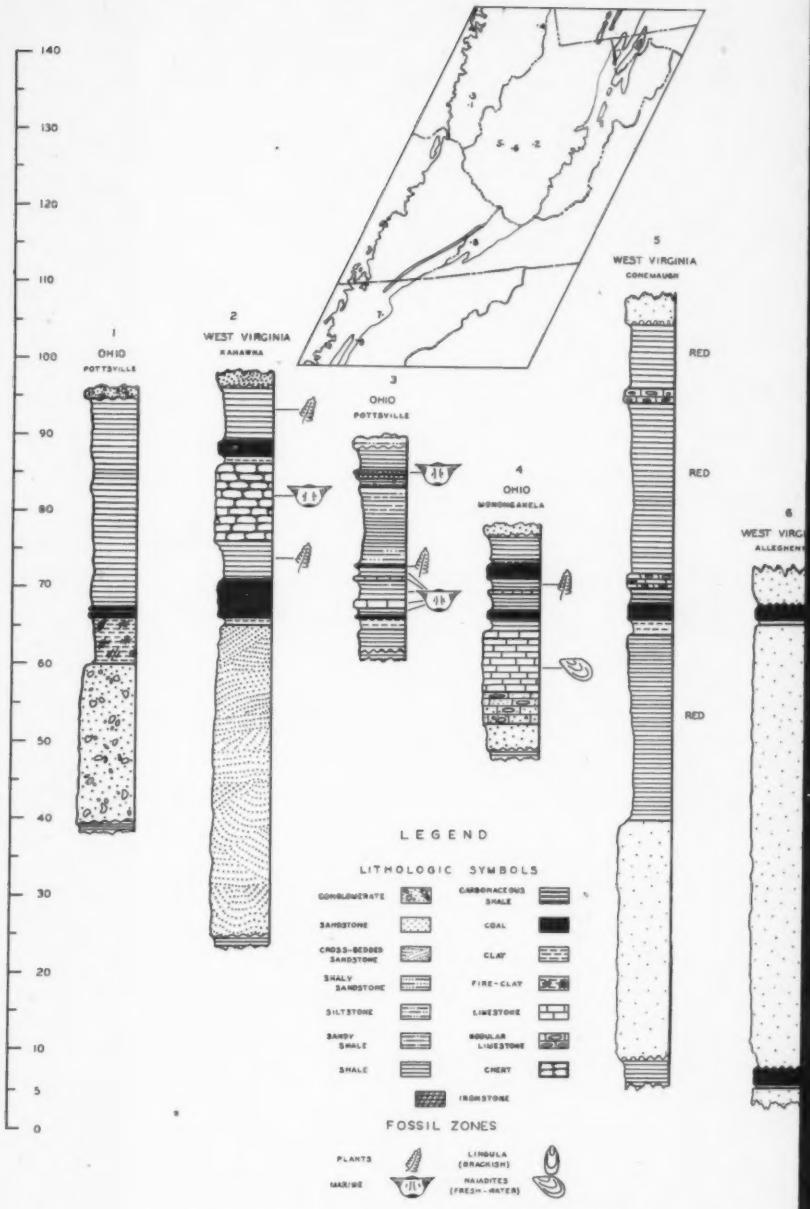
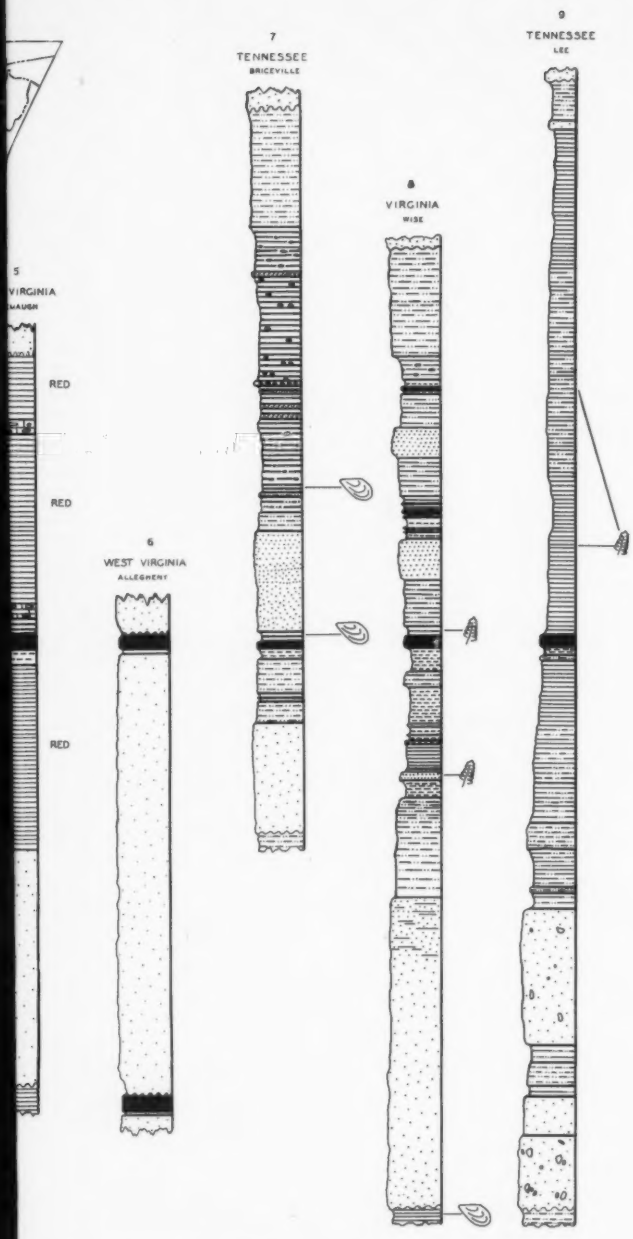


FIG. 1.—Types of cycles in the Pennsylvanian rocks of the Appalachian coal field.



alachian coal field. Titles of individual columns in text

areas represented. Correlation is not intended between the various columns, as the beds in them represent all the major groups of the Pennsylvanian. The columns have been drawn with the base of the coal at the same level near the middle of the column where coal is present. The assumed position of a coal horizon has been used to line up those columns which do not include coal beds. The columns are intended to illustrate how numerous kinds of rocks fit into a broadly generalized cyclic pattern. Each column is based on a particular outcrop section measured by the author or derived from the published literature. No effort was made to generalize or idealize the sequence for particular localities. The distribution of marine and nonmarine invertebrates and fossil plants, where known, is indicated by symbols.

TYPES OF PENNSYLVANIAN CYCLES IN THE APPALACHIAN COAL FIELD

The Appalachian Pennsylvanian is characterized by a predominance of clastic sediments, largely nonmarine; by an abundance of coal beds; and, in restricted areas, by refractory fire clays, flints, sedimentary iron ores, red beds, and fresh-water limestones. The cyclic successions range from more than 100 feet thick (Fig. 1, cols. 8 and 9) near the southeast border of the coal field to 25 feet or less (Fig. 1, col. 4) in Ohio and part of western Pennsylvania.

In Figure 1, column 1 illustrates the development of refractory fire clay in the position of the underclay (*d*) of Weller's Illinois cycle. The refractory clay may be of flint, semiflint, or plastic type. Refractory clays seem to be restricted to localities in which a part of the Pennsylvanian is thinner than normal, illustrating either very slow sedimentation or prolonged weathering between brief periods of sedimentation. The section shows the Sciotoville clay of southern Ohio of Pottsville age; but other refractory clays occur higher in the Pottsville and in the Allegheny in Ohio, northern West Virginia, Maryland, and Pennsylvania. The origin of these clays has been discussed by Wilber Stout[14] and others.

Column 2 (Fig. 1) illustrates the occurrence of bedded dark chert or flint in cyclic succession. The example shown is the Kanawha black flint of West Virginia, of Kanawha age. Other examples are the Flint Ridge flint of Kentucky and the Upper Mercer, Zaleski, Vanport, and Brush Creek flints of Ohio, of Pottsville, Allegheny, and Conemaugh ages. The flint yields a marine fauna, seems to occupy the position of the upper marine limestone (*i*) of Weller's cyclothem, and grades laterally into marine limestone (Vanport and Upper Mercer) or into black slaty shale (Kanawha). These flints are restricted in distribution in the Appalachian region but were extensively quarried by Indians as material for artifact construction, and they are useful marker beds in stratigraphic work. This column also illustrates what is called a "rider" coal, a thin additional coal above the main coal bed of a cycle, which apparently belongs in the same cycle with it.

Column 3 (Fig. 1) illustrates the thin "black-band" iron ores characteristic of the Pottsville and Lower Allegheny of the old Hanging Rock iron district of southern Ohio. The cycle shown includes the Lower Mercer limestone and Middle Mercer coal and indicates that the iron-ore bands belong above the main marine limestone of the cycle. They seem to correspond with the ironstone nodules and thin bands of the upper shale (*j*)

[14] "Origin of Coal Formation Clays," *Ohio Geol. Surv. Bull. 26* (4th ser., 1923), pp. 533–68.

of Weller's cyclothem. The ironstone beds ("black-band" ore) and nodules ("kidney" ore) seem to be somewhat commoner in dark-gray to black carbonaceous shales than in lighter shales. Some of the iron-ore bands contain marine fossils and other brackish or fresh-water invertebrates. Column 7 shows several levels of nodules and four thin bands in dark shale of the Briceville formation of Tennessee.

Column 4 (Fig. 1) illustrates the "fresh-water" limestones, which are perhaps the most conspicuous members of Upper Conemaugh, Monongahela, and Dunkard cycles in parts of east-central Ohio, northern West Virginia, and southwestern Pennsylvania. They seem to occupy the position of Weller's "fresh-water" limestone (*c*) beneath, rather than above, the coal beds. They differ, in that Weller's limestone is largely unfossiliferous, whereas the Appalachian fresh-water limestones contain a rich fauna of gastropods, pelecypods, ostracodes, and fish remains, all apparently of fresh-water facies. This facies has a prominent development near Washington, Pennsylvania, and Wheeling, West Virginia; but the limestones thin and disappear rather abruptly a little south of that area, along with the coal beds and plant-bearing shales, the succession giving way to red beds, as illustrated in column 5. This facies change affects later Conemaugh, Monongahela, and Dunkard beds. In the example in column 5 the Ames limestone and Harlem (?) coal are present near Charleston, West Virginia; but a little farther east the limestone becomes nonmarine, the coal thins out and disappears, and the cyclothem becomes almost entirely red shale and sandstone. At their northern margin the red beds seem to replace the sandy shale (*b*) of Weller's cycle, but the upper shale (*j*) and the sandstone (*a*) may also grade into red sediments.

Column 6 (Fig. 1) illustrates the Charleston sandstone near Charleston, West Virginia, which is formed by the union of the Roaring Creek, East Lynn, Freeport, Mahoning, and Buffalo sandstones of Kanawha, Allegheny, and Lower Conemaugh ages, the other strata of the normal succession largely disappearing. The composite character of the sandstone near Charleston may be recognized in that it is interrupted at about 50-foot intervals by thin but persistent coal beds and by lithologic differences between the sandstones above and below a particular coal. The No. 5 Block, Upper Kittanning, Lower Freeport, Upper Freeport, and Mahoning coals all seem to fall in this great sandstone mass. Although there are abrupt unconformable contacts at the bases of the several sandstones, there is no certainty that shales were deposited above each coal and subsequently eroded. The Charleston region may have been part of a large area of alluvial-fan or delta accumulation of sand, interrupted only briefly by coal-forming conditions throughout the later Kanawha, Allegheny, and early Conemaugh. Here the equivalents of Weller's beds (*a*) and (*e*) alone record the cycle.

Column 7 (Fig. 1) was chosen to illustrate thick, dark-gray to black upper shales yielding no fossils or occasional fresh-water pelecypods or brackish-water *Lingula* faunas. Plant remains are uncommon or absent. Although the dark shales are probably the counterparts of Weller's upper shale (*j*) and resemble them in containing ironstone nodules and bands, they were evidently deposited under conditions less favorable to the oxidation of organic matter. The scarcity of fossils in the dark shales suggests that the water may have been toxic to many

kinds of life-forms. The example is from the middle part of the Briceville formation of Tennessee above the Poplar Creek coal; but equally prominent dark shales occur in the Eastland shale of Tennessee, older than the Briceville; the Whetstone Creek shale and the shale above the Williamsburg coal of Kentucky; the Eagle shale; shales associated with the Douglas and Iaeger coals of southern West Virginia; and shales associated with the Quakertown coal of Ohio and Pennsylvania. Their period of greatest prominence seems to correspond with the Lampasas stage.

Column 8 (Fig. 1) illustrates a type of cyclic succession displayed in the Wise formation of Virginia; the Hance, Mingo, and Hignite formations of the Cumberland Gap coal field; and the Scott and Anderson formations of Tennessee. Here at the southeastern border of the coal field a thick, massive, basal sandstone is separated from the next similar bed by a shaly zone, generally containing two to ten benches of coal separated by shale, underclay, or even sandstone. Rapid sedimentation is attested by the finding of erect fossil casts of tree trunks rising several feet across shales or sandstones, in some places rooted in the top of a coal bed. The coal may be very thick and locally unparted, like the famous Pocahontas No. 3 bed at Pocahontas, Virginia, and may include zones of cannel coal. The outcropping succession in Wise County, Virginia, displays forty-four cycles of this type in beds of Lampasas age alone, with an average thickness of 68 feet, in contrast with Fulton County, Illinois, where the strata of Lampasas age display four cycles, averaging 10 feet.

Column 9 (Fig. 1) is representative of the Lee (Morrowan) of northern Tennessee and parts of Kentucky, Georgia, and Virginia, with a thick and locally conglomeratic basal sandstone overlain by a shaly coal-bearing, easily eroded zone. The example shows the Sewanee coal and conglomerate of southern Tennessee. Such a cycle as this includes two formations in the southern Tennessee system of nomenclature. The example drawn includes the Sewanee conglomerate and Whitwell shale. Overlying pairs of formations composing a cycle are (1) Herbert sandstone and Eastland shale, (2) Newton sandstone and Vandever shale, and (3) Rockcastle sandstone and Duskin Creek shale. The outcrops of this type of cycle give rise to plateaus, benches, or hills of circumdenudation bordered by talus-covered forested slopes on the shale outcrop and lower benches on the next lower sandstones.

TYPES OF PENNSYLVANIAN CYCLES IN THE MICHIGAN AND EASTERN INTERIOR BASINS

The Pennsylvanian rocks of the Michigan Basin (Fig. 2) are generally deeply covered with glacial till, and only one small area of outcrop seems to have had careful examination. This area, near Grand Ledge,[15] displays a section about 130 feet thick which Kelly divided into eight cyclical formations. The strata seem to be of Lampasas or Lower Des Moines age or both, judging from the fauna listed. Although there are individual differences in sequence in the eight cycles, the column drawn of cyclical formation *F*, the sixth from the base, shows general similarity to the sequence in western Illinois described by Weller, whose zones (*a*), (*b*), (*d*), (*e*), (*f*), (*h*), (*i*), and (*j*) are apparently all represented but by lesser thicknesses than are generally found in Illinois.

[15] W. A. Kelly, "Pennsylvanian Stratigraphy near Grand Ledge, Michigan," *Jour. Geol.*, Vol. XLI (1933), pp. 79–86.

In Figure 2, column 2 represents a type of cyclothem characteristic of the McLeansboro of northern Illinois. The example shown includes the La Salle limestone, the thickest marine Pennsylvanian limestone of northern Illinois. Other cyclothems—the Little Vermillion above the La Salle and the Hall, Hicks, and Turner below—differ principally in having a thinner limestone, averaging about 2 feet instead of 25 feet thick. This group of cyclothems lacks a basal sandstone and a fresh-water limestone and has thin coal and thin, largely calcareous underclay. It consists mostly of beds (*g*), (*h*), (*i*), and (*j*) of Weller's cyclothem.

Column 3 (Fig. 2), which represents the Trivoli cyclothem and includes coal No. 8, Lower McLeansboro, of western Illinois, is quite representative of Weller's typical cyclothem. Bed (*b*), sandy shale, is absent or very thin; bed (*f*), nonmarine shale, is absent; and the "fresh-water" limestone (*c*) is represented by somewhat infrequent limestone nodules in calcareous clay.

Column 4 (Fig. 2), the Liverpool cyclothem, including the Colchester (No. 2) coal of the Lower Carbondale, western Illinois, resembles the preceding in most respects but illustrates a thick development of the nonmarine shale (*f*), with no marine limestone in the position of Weller's bed (*g*), i.e., between the black slaty shale (*h*) and the coal. The black slaty shale may contain large, oval, cannon-ball or irregularly shaped concretions, locally called "niggerheads." The upper marine zone (*i*) is here characterized by an alternation of several thin bands of limestone and shale, the Oak Grove member, each with distinctive lithology and fauna, rather than by a single bed of limestone. The nonmarine shale (*f*) shows marked local variability, ranging from 20 feet to a few inches within less than a mile. It is equivalent to the stratum containing concretions in northern Illinois, which yield the well-known Mazon Creek flora.

Column 5 (Fig. 2) is typical of the Carbondale and Lower McLeansboro of the Ozark flank region of western and southwestern Illinois. The column illustrated is the Brereton cyclothem, in Brown County, which here consists of underclay (*d*), a sooty film representing the Herrin (No. 6) coal, which is 4–11 feet thick elsewhere in Illinois, and the marine limestone (*h*). The underclay of the next cyclothem overlies the Brereton limestone; and the marine St. David limestone, cap of the Springfield (No. 5) coal, is below the underclay of the No. 6 coal. Here only 5 or 6 feet record a widespread cyclothem, which is generally 30–60 feet thick. This condition obtains in Adams, Brown, and Calhoun counties west of the Illinois River and in Greene, Jersey, Madison, St. Clair, and Randolph counties opposite St. Louis, as well as in the Pennsylvanian outlier in and near St. Louis, Missouri.[16] The slight thickness probably results from weak positive tendencies of the Ozark region during Carbondale and McLeansboro time, but the fine texture of the sediment indicates that the Ozark dome was not a source area for much sediment.

Column 6 (Fig. 2) represents a column near Alton, Madison County, Illinois, in the St. Louis region, in which six cyclothems representing Lampasas and early Des Moines time show a composite thickness of only about 40 feet. These much-reduced cyclothems are correlated tentatively, from the base up, with the Baby-

[16] J. Brookes Knight, "The Location and Areal Extent of the St. Louis Pennsylvanian Outlier," *Amer. Jour. Sci.*, Vol. XXV (5th ser., 1933), pp. 25–48, 166–78.

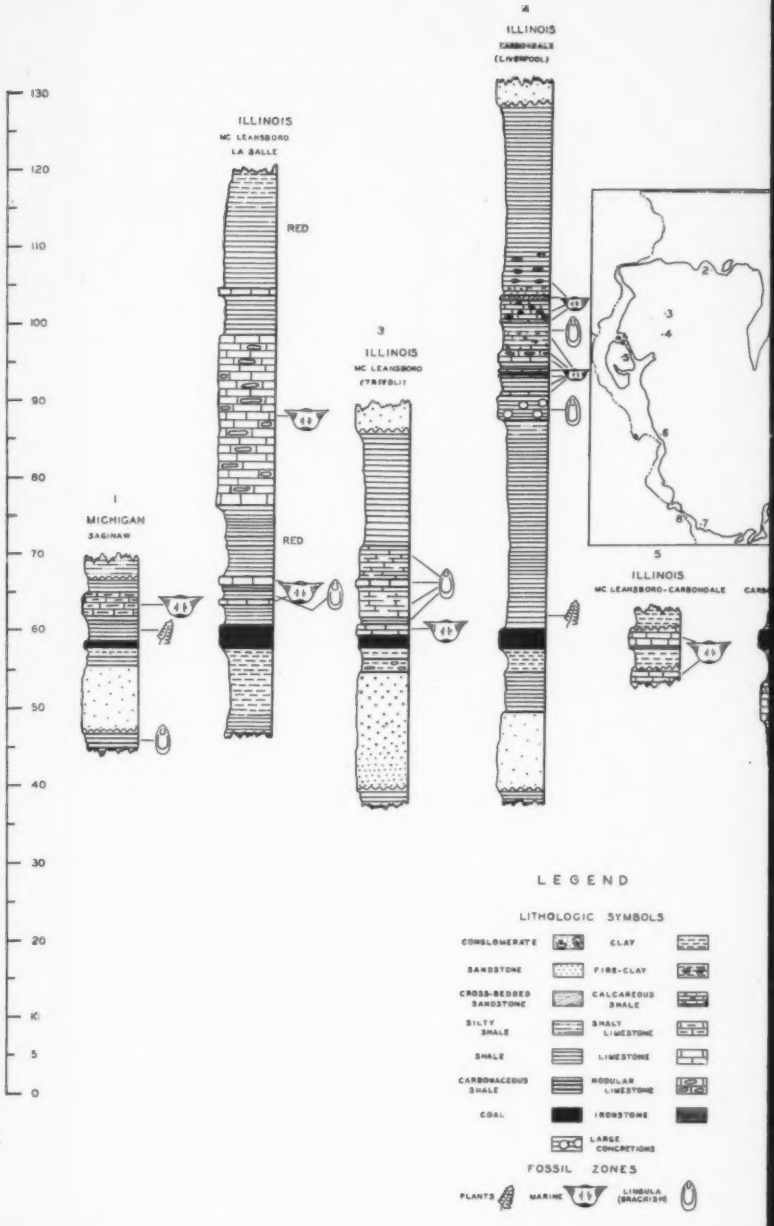
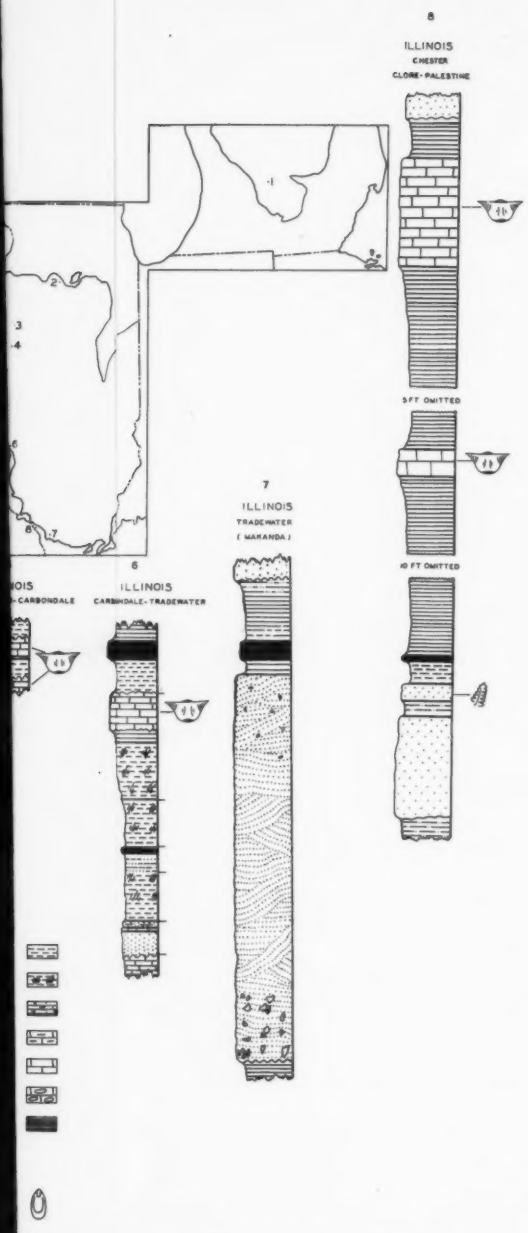


FIG. 2.—Types of cycles in the Pennsylvanian rocks of the Michigan and eastern Interior basi



interior basins and later Mississippian in southern Illinois

lon, Pope Creek, Seville, De Long, Seahorne, and Liverpool cyclothems. The most conspicuous feature of the succession is refractory fire clay, which is known as the "Cheltenham clay" in the St. Louis region. Thin smut streaks in the clay seem to mark the positions of the Pope Creek, De Long, and Seahorne coals. The slightly thicker Seville coal and the marine Seahorne limestone also wedge out in part of the St. Louis region, the fire clay then extending from the Pope Creek up through the De Long, Seahorne, and Liverpool clays to the base of the No. 2 coal. This association of refractory clay with slow sedimentation has been previously noted in Figure 1, column 1, for the Appalachian region; and similar successions prevail in Lincoln and Audrain counties, Missouri, and in La Salle and Grundy counties, northern Illinois.

Column 7 (Fig. 2) represents a type of cyclothem which is common in the Lower Tradewater and Caseyville of southern Illinois, Indiana, and western Kentucky. The column is the Makanda sandstone and overlying underclay, coal, and shale from Jackson County, Illinois; but several successions above and below this are quite similar. The basal sandstone is thick and may be conglomeratic. The underclay is thin and shaly, the coal is thin and discontinuous, and the overlying shales are nonmarine and may be truncated by the next-overlying sandstone. It somewhat resembles the southern Appalachian Lee cyclothem (Fig. 1, col. 9).

Column 8 (Fig. 2) illustrates cyclical sedimentation in the Chester (later Mississippian) of southern Illinois. This series consists of sixteen formations, eight pairs of sandstone and marine shale-limestone alternations, as follows, from the base up: (1) Aux Vases–Renault, (2) Bethel–Paint Creek, (3) Cypress-Golconda, (4) Hardinsburg–Glen Dean, (5) Tar Springs–Vienna, (6) Waltersburg-Menard, (7) Palestine-Clore, the pair shown in this column, and (8) Degonia-Kinkaid. Coal is rarely more than a few inches thick and less persistent than Pennsylvanian coals, but the succession seems to record eight distinct cyclic alternations, with an average of about 100 feet in each. The sandstones are finer grained and more quartzitic, and the limestones are generally thicker and more fossiliferous, than in the Illinois Pennsylvanian.

TYPES OF PENNSYLVANIAN CYCLES IN THE MID-CONTINENT REGION

In Figure 3, column 1 is somewhat representative of the Upper Des Moines of southern Iowa. The cyclothem shown includes the Mystic coal and corresponds with the Brereton cyclothem of Illinois. The succession differs from that for the same cyclothem in western Illinois, in that the Cuba sandstone of western Illinois has graded to sandy shale, and a marine limestone, the Higginsville, beneath the coal, seems to be the counterpart of the "fresh-water" limestone below the No. 6 coal of Illinois. This change of Weller's bed (*c*) from a "fresh-water" to a marine limestone is quite characteristic of the mid-continent region. Columns 3 and 4 of this figure show other examples of these lower marine limestones.

Column 2 (Fig. 3), in Nebraska, shows that the upper marine limestone (Weller's [*i*]) is greatly expanded and that there is no coal, little underclay, and no basal sandstone. The nonmarine part of the cycle here is red shale in place of sandy and micaceous shale above sandstone. The equivalent of the underclay in this and the succeeding columns can be

recognized as a nonlaminated shale below laminated shale, rather than by the slickensides and root traces which characterize it farther east. The cycle illustrated includes the Iatan limestone at the top of the Missouri group.

Column 3 (Fig. 3) is representative of the Marmaton (Upper Des Moines) type of cycle of Missouri and eastern Kansas.[17] It is simpler than the megacyclothem and somewhat intermediate between it and Weller's Illinois cyclothem, indicating that the megacyclothem probably represents the same magnitude of time as the Illinois cyclothem and not a grouping of the latter. The example shown includes the Altamont limestone in north-central Missouri.

Column 4 (Fig. 3) represents Moore's megacyclothem, typically developed in the Shawnee group of Virgil age, with virtually no coal or underclay, little sandstone, and several zones of marine limestone and shale, which are much more prominent than in Illinois.[18] The example shown includes the Oread limestone and the lower part of the Kanwaka shale above and the upper part of the Lawrence shale below. The five marine limestones shown probably correspond with beds of the Illinois cyclothem as follows: (1) the lowest limestone below the underclay seems equivalent to the "freshwater" limestone (*c*); (2) the second limestone between the underclay and the black slaty shale is bed (*g*) of Weller's cyclothem and is the most uniform in thickness and characteristics of any member of the Kansas megacyclothem, though rarely found and quite variable in Illinois; (3) above the black slaty shale is the thickest limestone, corresponding with (*i*) of the Illinois cyclothem; (4) a little above, the main marine limestone may be equivalent to the calcareous shale or "clod" above the Illinois marine limestone (*i*); (5) the uppermost limestone is well within the thick upper shale (*j*) and may be equivalent to occasional thin limestones in Illinois, which occur in the upper shale. The St. David cyclothem of Carbondale age has such a limestone in Fulton and Peoria counties, western Illinois.

In column 5 (Fig. 3), in the Marmaton of northern Oklahoma, the limestone is thicker than in Missouri (col. 3), and each limestone tends to cap an eastward-facing escarpment. The coal and underclay are absent, and the lower marine limestone of column 3 may have graded into a sandstone, the upper of the two sandstones shown. The limestone shown is the Pawnee, near Nowata, Oklahoma.

South of the Arkansas River in Oklahoma the section thickens tremendously with the introduction of clastic units and the thinning and disappearance of limestones. Coals are not so frequent as in somewhat comparable clastic successions of West Virginia, Kentucky, and southern Illinois; but there is a coal in the example illustrated in column 6 (Fig. 3), from the Hartshorne sandstone formation. Somewhat similar sequences, but generally with slightly more marine beds and less coal, are found in the McAlester, Savanna, Boggy, Thurman, Stuart, and Senora formations.[19] The individual cyclic successions in some instances are several hundred feet thick.

Conditions in north-central Texas are

[17] John M. Jewett, "Classification of the Marmaton Group, Pennsylvanian, in Kansas," *Univ. Kan. Pub., Kan. State Geol. Surv. Bull. 38*, Part XI (1941), pp. 285–344.

[18] R. C. Moore, "Stratigraphic Classification of the Pennsylvanian Rocks of Kansas," *Univ. Kan. Bull. 22* (1935), p. 32.

[19] C. H. Dane, H. E. Rothrock, and J. S. Williams, "Geology and Fuel Resources of the Southern Part of Oklahoma Coal Field. III. The Quinton-Scipio District," *U.S. Geol. Surv. Bull. 874-C* (1938), pp. 157–68.

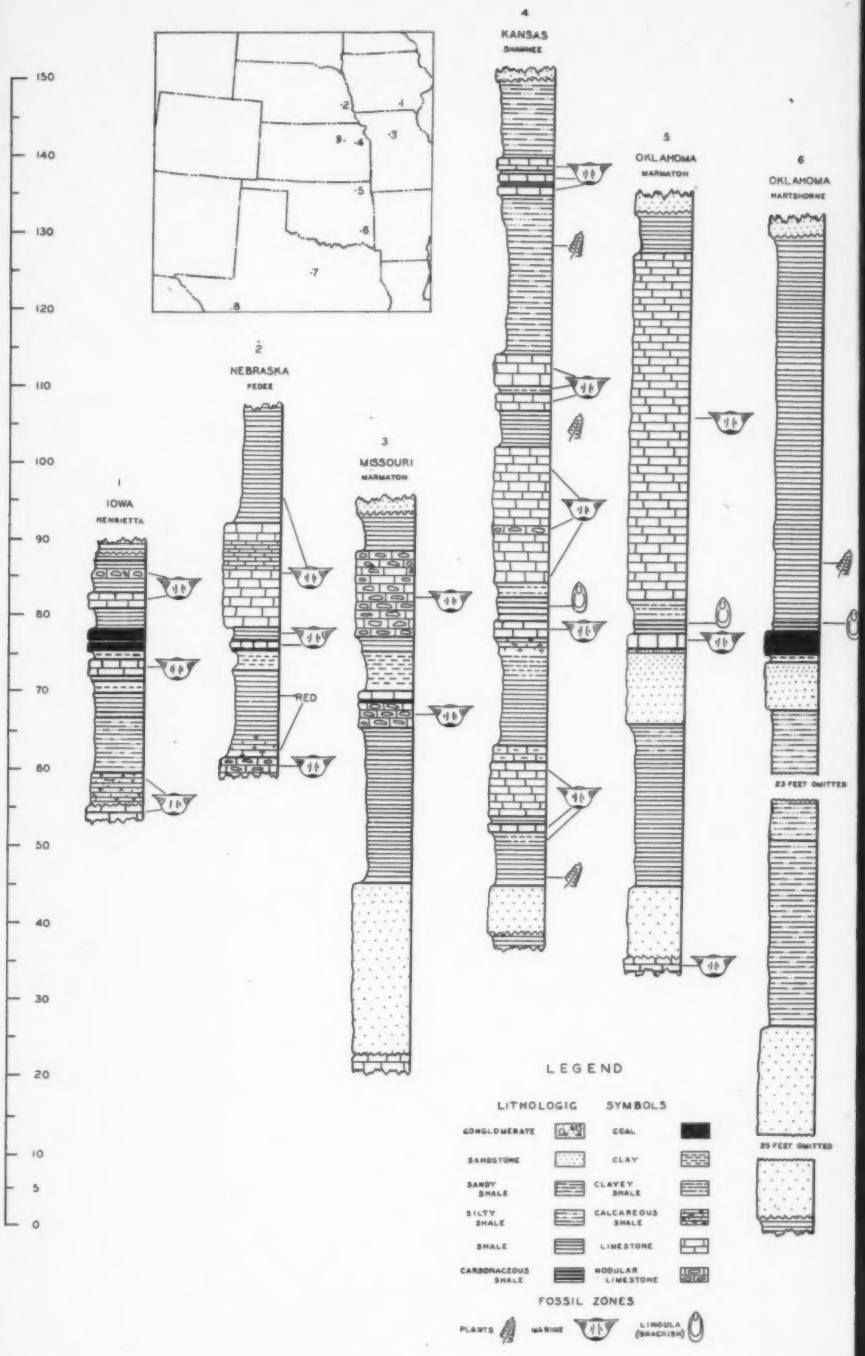
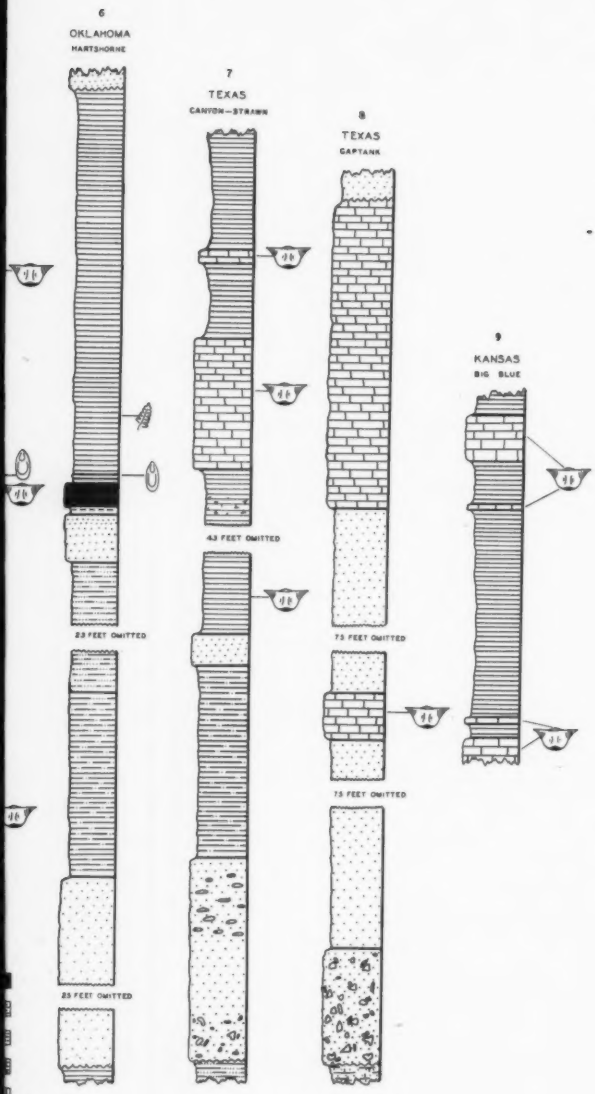


FIG. 3.—Types of cycles in the Pennsylvanian rocks of the mid-continent region and of



inent region and of the Lower Permian of Kansas

somewhat like those in southern Oklahoma, but the succession is thinner, and coal is less common.[20] The example shown in column 7 (Fig. 3) includes the Palo Pinto limestone and underlying shale and sandstone at the top of the Strawn and the base of the Canyon formations of Missouri age. As in northeastern Oklahoma, the limestones, where sufficiently thick, tend to cap eastward-facing escarpments. The disappearance of coal in this and most columns farther west was perhaps due to somewhat less humidity than in the eastern states, where coal is more prominent.

Column 8 (Fig. 3) represents beds of Gaptank age in the Marathon Basin, western Texas.[21] It is somewhat similar to column 7 from north-central Texas, but the limestone is thicker; there are no argillaceous beds, or only a slight thickness of them; and some of the sandstones are conglomeratic, containing slightly weathered, poorly rounded fragments, which were evidently locally derived. This type of sediment, which is also widespread in the southern Rocky Mountains, results from the fact that the depositional basins were nearer land areas that possessed some relief than were the basins farther east.

Column 9 (Fig. 3) represents a type of cycle found in the Big Blue series, Lower Permian, of Kansas and Nebraska.[22] It consists wholly of marine shale and limestone but shows a definite cyclical pattern in the lithology and fauna of the shales and limestones. It may be contrasted with Figure 1, column 9, and Figure 2, column 7, both of which are wholly nonmarine.

TYPES OF PENNSYLVANIAN CYCLES IN THE ROCKY MOUNTAINS

In the Rocky Mountains the Pennsylvanian lacks coal, carbonaceous shale, underclay, and "fresh-water" limestone almost entirely, and shale and ironstone are uncommon (Fig. 4). Although the lithology at most places exhibits a pattern suggestive of some sort of rhythmic deposition, detailed studies by C. B. Read and others in New Mexico show that the cyclic units are much less widespread than in the central and eastern United States, and thin members have not yet been widely traced and correlated anywhere in the Rocky Mountains. Although this greater variability may result from localized lands with high relief adjoining local depositional basins in parts of the Rocky Mountains, elsewhere it probably reflects less detailed stratigraphic studies than have been carried on farther east; and the numerous fossiliferous zones in such areas as the Hartville Uplift, the Black Hills, the Laramie Range, central and western Colorado, and the San Juan Mountains of southwestern Colorado would seem to offer the opportunity for precise correlation of thin members through large areas after adequate sections have been carefully studied lithologically and faunally.

In Figure 4, column 1 represents a type of alternation in the "Brazer" limestone, later or Middle Mississippian of western Wyoming. The sequence displays dense, dark, lithographic, nearly unfossiliferous limestone, overlain by lighter or pinker limestone breccia with angular or subangular limestone pebbles. Several such alternations seem to be per-

[20] F. B. Plummer and Joseph Hornberger, Jr., "Geology of Palo Pinto County, Texas," *Univ. Tex. Bull. 3534* (1935), pp. 31–32.

[21] Philip B. King, "The Geology of the Glass Mountains, Texas. I. Descriptive Geology," *Univ. Tex. Bull. 3038* (1930), p. 44.

[22] John M. Jewett, "Evidence of Cyclic Sedimentation in Kansas during the Permian Period," *Trans. Kan. Acad. Sci.*, Vol. XXXVI (1933), pp. 137–40.

sistent in the Gros Venture, Teton, Hoback, Wyoming, and Snake River ranges of western Wyoming and eastern Idaho. Their significance is not known. It has been suggested[23] that the breccias may be founder breccias resulting from the solution of interbedded gypsum or anhydrite, but no field evidence in support of this theory has been discovered.

Column 2 (Fig. 4), characteristic of the Tensleep and Quadrant formations of northwestern Wyoming and adjacent parts of Montana, consists of a two-member alternation of dense, hard, well-sorted quartzitic sandstone and light-gray to white, dense, somewhat cherty, dolomitic limestone. Although this type of alternation appears in several mountain ranges, the individual pairs of beds have not yet been traced between ranges, so that it is not known whether the cycle records local or widespread fluctuations of some sort. Minor erosional unconformities with a relief of a few inches are common at the bases of the sandstones. Many of the limestones and dolomites are wholly unfossiliferous, and fossils are rare and fragmentary throughout the section.

Columns 3, 4, and 5 (Fig. 4) show, respectively, representative alternations in the Minnelusa formation, Black Hills, South Dakota; the Guernsey formation, Hartville Uplift, Wyoming; and the Casper formation, Laramie Range, Wyoming. The Black Hills and Laramie Range sections show alternations of marine fossiliferous limestones with sandstones, the sandstones in the Laramie Range being conglomeratic in some cycles. In the Hartville area the alternation is between limestone and red calcareous shale.

Column 6 (Fig. 4) is representative of the Fountain formation of the Denver region and was measured at Red Rocks Park, Morrison, Colorado. Here the Fountain formation, which seems to be wholly nonmarine and barren of all fossils, displays an alternation of pink arkosic conglomerate and maroon shale, with evidence of slight disconformity at the top of each shale. There is no way to determine whether these alternations correspond approximately with cyclothems of the eastern states, nor is it known whether the pairs of beds achieve wide areal extent within the Denver-Colorado Springs region.

Columns 7 and 8 (Fig. 4) are in the Salida region, southern Colorado, on the east side of the Sangre de Cristo Range. In that region the lowest few hundred feet of the Weber formation, equivalent to the Glen Eyrie beds of the Colorado Springs area, contain quartzose sandstone, underclay, thin coal, and plant-bearing nonmarine shales (col. 8), the whole succession resembling that in the Lower Pennsylvanian of western Illinois. Similar beds occur in the Lower Pennsylvanian near Pecos, New Mexico. These are the only Rocky Mountain Pennsylvanian beds displaying carbonaceous sediments like those in the eastern states. Above these beds the succession changes abruptly to a type of cycle repeated many times in the Upper Weber and Maroon formations (col. 7). This succession includes arkosic conglomerate, sandstone, and marine limestone, with comparatively little clay shale and no coal or underclay. This succession resembles that of other parts of the southern Rocky Mountains (cols. 9, 11, and 12), but with variations in the coarseness of conglomerate or sandstone. The change in character between columns 7 and 8 at the same locality may be attributed to a decrease in humidity, so that the rocks in the upland

[23] M. Y. Williams, personal communication.

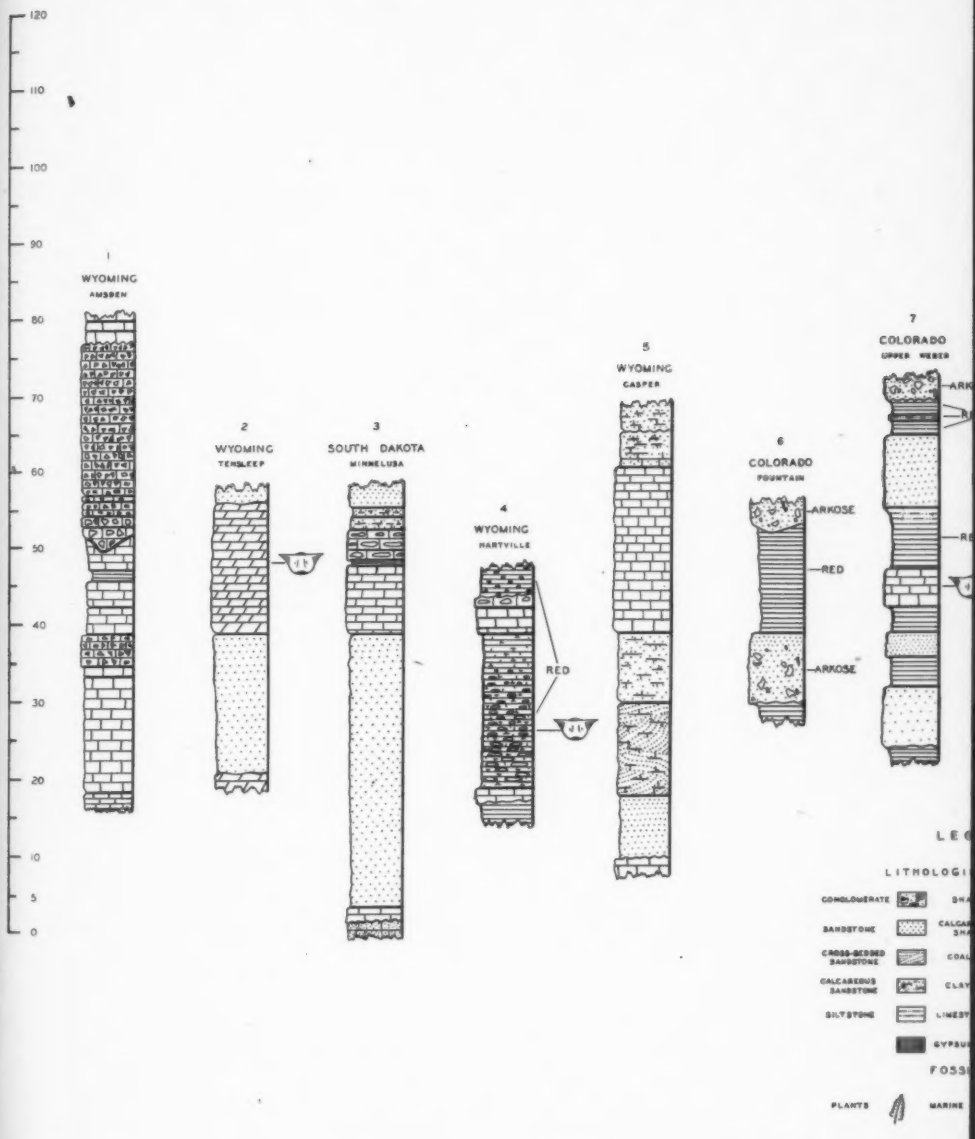
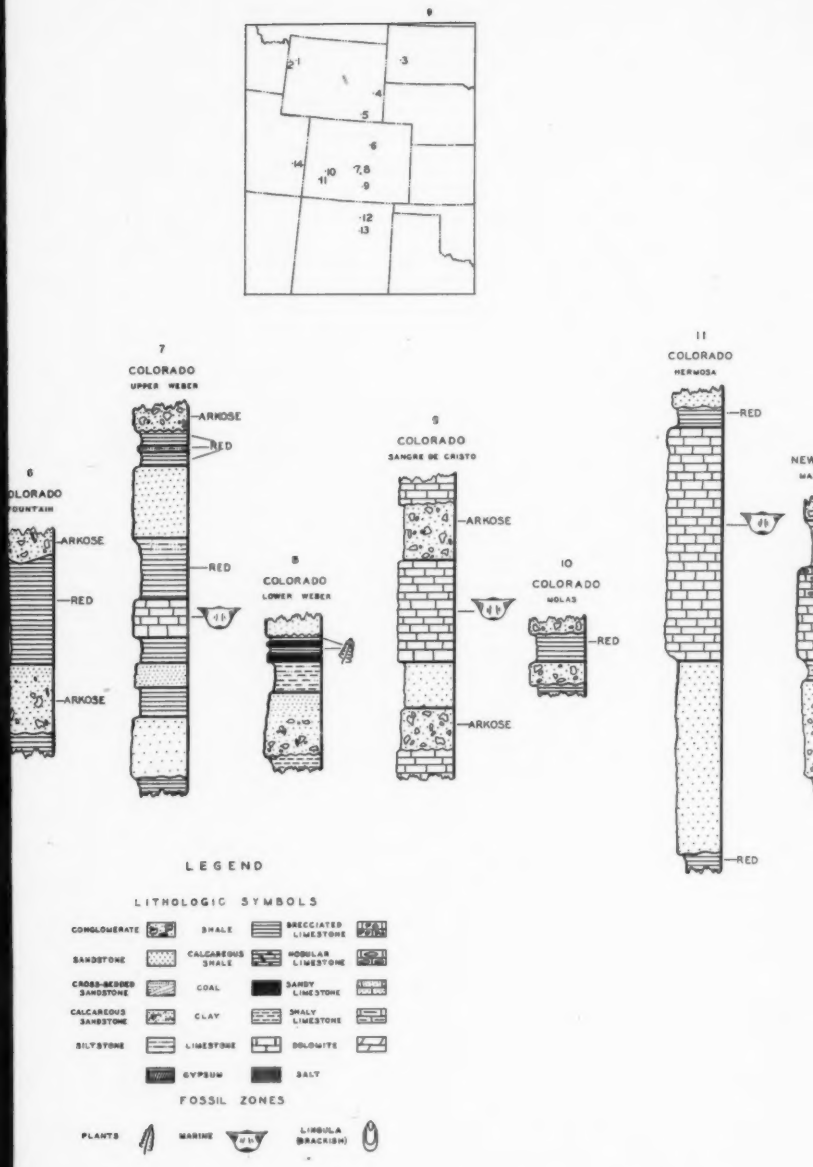
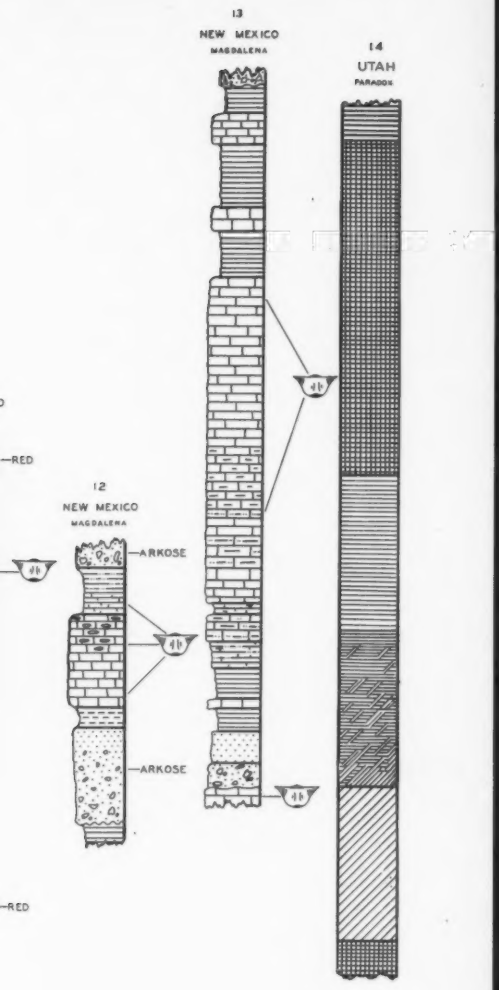


FIG. 4.—Types of cycles in the Pennsylvanian rocks of the Ro



ylvanian rocks of the Rocky Mountains and the Mississippian (Amsden) of Wyoming


13
NEW MEXICO
MAGDALENA
14
UTAH
PARADOX
12
NEW MEXICO
MAGDALENA
ARKOSE
ARKOSE
RED
RED

areas supplying sediment to this basin were weathered more physically than chemically.

Column 9 (Fig. 4) is in the Sangre de Cristo formation at La Veta Pass, Colorado, farther south in the Sangre de Cristo Range. Some of the conglomerates of this region are very coarse, the individual cobbles reaching a maximum size of about 6 feet. Many of the fragments are granite or fresh feldspar.

Column 10 (Fig. 4) represents the Molas formation, Lower Pennsylvanian, in the San Juan Mountains, southwestern Colorado. This formation, although thin on the outcrop, shows several alternations of thin, nonarkosic, round-pebble conglomerates with red shales, in what seems to represent some sort of cyclic deposition. The succession is unfossiliferous and resembles that of the Fountain formation near Denver (col. 6) except that the Fountain formation is arkosic and the pebbles are generally more angular than those in the Molas conglomerates.

Column 11 (Fig. 4) is representative of the Hermosa formation, overlying the Molas in the San Juan Mountains. It is somewhat similar to the Sangre de Cristo section at La Veta Pass (col. 9) except that the sandstones are finer grained and generally nonconglomeratic.

Column 12 (Fig. 4) is from the southern part of the Sangre de Cristo Range near Taos, New Mexico, where the strata are referred to the Magdalena formation. Although the individual beds of the Taos succession are reported to be quite lenticular, there appear to be at least eighty cycles, averaging 60–80 feet thick. Like the La Veta Pass section (col. 9), some of the conglomerates include cobbles as large as 6 feet in dimension. There are, however, more numerous and more prominent marine fossiliferous limestones than in the La Veta Pass area.

Column 13 (Fig. 4) is from the Magdalena formation near Pecos, New Mexico. The succession differs from that at Taos (col. 12) in that the sandstones and conglomerates are thinner and finer grained and the limestones are thicker. The limestones here produce prominent benches and escarpments, as they do in parts of Texas and Oklahoma.

Column 14 (Fig. 4) represents a portion of the Paradox formation near Moab, eastern Utah, between the Molas (below) and the Hermosa formations. The column is based on a partial section taken from a diamond-drill core.[24] The core record seems to indicate a fairly regular cyclic repetition of shale, limestone, gypsum, and salt through a total thickness of about 6,000 feet. This is the only cycle that includes important evaporite beds and may not in any way correspond to the other cyclic successions included in Figure 4. The salt is interpreted as the final unit of the cycle, followed by shale with an increase in the amount of sediment washed into the barred basin in which the Paradox formation was deposited.

There are, no doubt, other areas exhibiting still other types of cyclic deposition, such as the cycle described from the Permian Kaibab limestone of the Grand Canyon region.[25]

Regions studied by the author that do not seem to display any form of cyclic sedimentation are southeastern Idaho, where the Wells formation is nearly solid limestone, and the Wasatch Moun-

[24] A. A. Baker, "Geology and Oil Possibilities of the Moab District, Grand and San Juan Counties, Utah," *U.S. Geol. Surv. Bull. 841* (1933), p. 86.

[25] Edwin D. McKee, "The Environment and History of the Toroweap and Kaibab Formations of Northern Arizona and Southern Utah," *Carnegie Inst. Wash. Pub. No. 492* (1938), pp. 129–32.

tains of Utah, where the Weber formation is mostly uniform fine-grained quartzitic sandstone. The Naco formation of southeastern Arizona may or may not be cyclic but is not classified here because it has not been seen by the author. It is mostly limestone. Little information is at hand as to the cyclic or noncyclic character of Pennsylvanian sediments in the Great Basin, Canadian Rockies, and Pacific Coast areas.

PERSISTENCE OF PENNSYLVANIAN BEDS

The remarks thus far have stressed the vertical and lateral heterogeneity of the Pennsylvanian system. It should be noted in contrast that some very thin beds attain almost unbelievable lateral extent. For example, the fire-clay coal of eastern Kentucky and its correlatives in other states have a 4–6-inch parting of flint fire clay, which has been traced through considerable portions of the West Virginia, Virginia, Kentucky, and Tennessee fields.[26] Even more extensive is the parting known as the "Blue Band" in the Herrin (No. 6) coal of Illinois. This and one or two other thinner partings are found wherever the coal is known and at some places in Illinois, Indiana, western Kentucky, Iowa, and Missouri, where the coal itself is represented only by smut streaks; and available evidence suggests that the coal may be equivalent to the Middle Kittanning of Ohio, Pennsylvania, eastern Kentucky, and West Virginia, which at most places displays a similar succession of thin partings. The average thickness of the individual partings in this coal is less than 2 inches, and in some places the thinnest is plainly recognizable with a thickness less than $\frac{1}{4}$ inch.

[26] H. R. Wanless, "Pennsylvanian Correlations in the Eastern Interior and Appalachian Coal Fields," *Geol. Soc. Amer., Spec. Paper 17* (1939), pp. 55–57.

A 2–6-inch band of cone-in-cone attached to the principal limestone bed of the Oak Grove member, Liverpool cyclothem, has been traced from the Rock Island region of northwestern Illinois to the Terre Haute region of western Indiana. The Covel conglomerate,[27] a bed of limestone conglomerate 1–6 inches thick between coals Nos. 4 and 5, has been found at many localities in Iowa, Illinois, and Indiana. Many other examples of the great persistence of thin beds could be cited, especially from the eastern Interior and mid-continent areas.

GRAPHIC REPRESENTATIONS OF VARIATIONS IN PENNSYLVANIAN LITHOLOGY

It seems that some suitable method might be devised to show graphically the nature of lateral change in lithology of the Pennsylvanian and its subdivisions. In approaching this problem the author prepared a sheet (Fig. 5) to record data pertaining to the lithology of Pennsylvanian rocks of a limited area. A preliminary count showed that data pertaining to the Pennsylvanian might be available for about eleven hundred counties in which the system either outcrops or lies at a sufficiently moderate depth to be readily accessible to the drill. It was therefore decided to use the county as the unit of variation except where a county is divided into segments by a major structural feature like the La Salle anticline of Illinois or the Pine Mountain thrust fault, in which cases two or more sheets are prepared for a county. The sheet provides a place to record the locality, source of data and reliability of the column; the age of overlying strata, if any, and strata immediately below the

[27] H. B. Willman, "The Covel Conglomerate, a Guide Bed in the Pennsylvanian of Northern Illinois," *Trans. Ill. Acad. Sci.*, Vol. XXXII (1939), pp. 174–76.

DATA SHEET, PENNSYLVANIAN LITHOLOGY

State: W. VIRGINIA *County:* KANAWHA *Locality of column:* COMPOSITE—FROM SIX COLUMNS
Reliability: GOOD *Reference:* *W.Va. Geol. Surv. County Repts., Kanawha County*
Overlying stratum: DUNKARD PERMIAN *Substratum:* MAUCHCHUNK MISSISSIPPIAN

	Rock Type	Virgil			Missouri			Des Moines			Lampasas			Morrow			Stanley Jackfork			Total		
		N.	T.	%	N.	T.	%	N.	T.	%	N.	T.	%	N.	T.	%	N.	T.	%	N.	T.	%
V	Arkosic cgl.																					
M	Quartz cgl.										2	4′	0.7	6	72′	7.9	1	1′	0.2	9	76′	2.4
	Sandstone	8	228′	43.2	6	225′	65.2	8	435′	89.1	14	271′	51.5	19	607′	67.5	4	155′	42.6	59	1,921′	61.4
	Red ss.																					
	Oil zone																					
	Plant sh.	11	166′	32.9	3	62′	17.9	2	20′	4.2	16	128′	24.6	11	166′	18.4	4	111′	30.5	47	654′	21.
	Marine sh.										3	25′	4.7							3	25′	0.8
	Black slate																					
	Dark shale	1	1′	0.1							6	53′	10.1	7	53′	5.9	5	97′	26.4	19	203′	6.5
	Red shale	9	102′	21.9	4	48′	13.9													13	150′	4.8
	Fire clay							1	6′	1.3										1	6′	0.2
D	Underclay	2	5′	1.1	3	6′	1.7	2	3′	0.6	5	5′	1.0				1	3″	0.1	19	19′	0.6
	F.W. ls.																					
	Marine ls.				1	2′	0.6				4	4′	0.8							5	6′	0.2
	Fusulinid																					
	Dolomite																					
	Cherty ls.																					
L	Chert							1	4′	0.8										1	4′	0.1
	Coal	1	5′	0.9	2	2′	0.7	7	18′	3.7	14	35′	6.6	3	3′	0.3	2	7″	0.2	29	63′	2.
	Iron ore																					
M	Gypsum																					
	Salt																					
	Lava																					
	Pyroclastic																					
SJ	Schist																					
	Gneiss																					
	Total	32	507′	100	19	346′	100	21	46′	100	64	524′	100	46	901′	100	17	364′	100	199	3,128′	100
	Cycles	11			5			5			13			5			5			44		

Monongahela | Conemaugh | Allegheny | Kanawha | New River | Pocahontas | Princeton

FIG. 5.—Data sheet for Kanawha County, West Virginia, recording proportions of various rock types in the Pennsylvanian column for this country

Pennsylvanian; the part of the total Pennsylvanian column represented in the county in terms of the major subdivisions used in the National Research Council Committee report—Virgil, Missouri, Des Moines, Lampasas, and Morrow—with the addition of a basal Pennsylvanian or Pennsylvanian-Mississippian unit, here called the "Stanley-Jackfork," the names locally applied to principal subdivisions; and the number of beds (N), total thickness (T), and percentage (%) of 26 kinds of rocks in each of the divisions, as well as in the total Pennsylvanian section for the county. The beds comprising each of these divisions are determined in accordance with the correlation chart accompanying the report of the Pennsylvanian subcommittee.[28] If the section is cyclic, the number of cyclic units in each subdivision of the Pennsylvanian is recorded. With intensive application for about 1 month and with student assistance,[29] made available by the University of Illinois graduate school, data sheets like that in Figure 5 have been prepared for about one hundred and sixty counties, including all the Pennsylvanian areas of Georgia, Tennessee, Virginia, West Virginia, and Maryland and parts of eastern Kentucky, Ohio, Illinois, and Missouri. Further studies of this type are contemplated, directed toward the completion of data sheets for all Pennsylvanian areas in the United States. Assistance will be greatly appreciated in the form of access to detailed descriptions of the Pennsylvanian of any area from outcrops, core descriptions, or sample studies. Such sources have been used almost exclusively except in northwestern West Virginia and parts of eastern Kentucky, where the best available information on part of the subsurface Pennsylvanian was in the form of drillers' logs of oil wells. Some difficulty has been experienced in classifying shales as plant (nonmarine), marine, or dark. Some records and descriptions fail to mention underclays and thin coals, while others undoubtedly refer to some common shales as fire clays. The pebbly character of thick massive sandstones is generally better indicated in outcrop descriptions than in subsurface records. The sheet displayed (Fig. 5) represents Kanawha County, West Virginia, the only county thus far encountered in which the entire Pennsylvanian seems to be recorded. The range in length of column is from 10 feet in Whiteside County, northwestern Illinois, where a sandstone of Des Moines age fills a channel cut in Silurian dolomite, to Wise County, Virginia, where there are 7,088 feet extending up from the base of the Pennsylvanian only about as high as the 10-foot sandstone of Whiteside County. In Wise County, where excellent outcrops and core-drill records are the source of information, there are 88 coal beds, aggregating 132 feet 6 inches and totaling 1.8 per cent of the Pennsylvanian column; 112 sandstones, aggregating 2,412 feet; and 152 nonmarine shales, totaling 3,396 feet. In contrast, there is only one marine limestone, 8 inches thick; and there are 6 marine shales (fossil-bearing), totaling 66 feet.

The figures representing numbers of beds, total thickness, and percentage can be plotted and contoured as lithologic-variation maps, and the total thickness of each division of the Pennsylvanian can be used to prepare isopach maps.

Since most of the available time has

[28] R. C. Moore and others, "Correlation of Pennsylvanian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), chart opp. p. 706.

[29] The service rendered by Miss Lorena Ross and Mr. Robert Knodle, research assistants, and Miss Norma Wallis, draftsman, aided greatly in compiling the data and preparing the illustrations accompanying this paper.

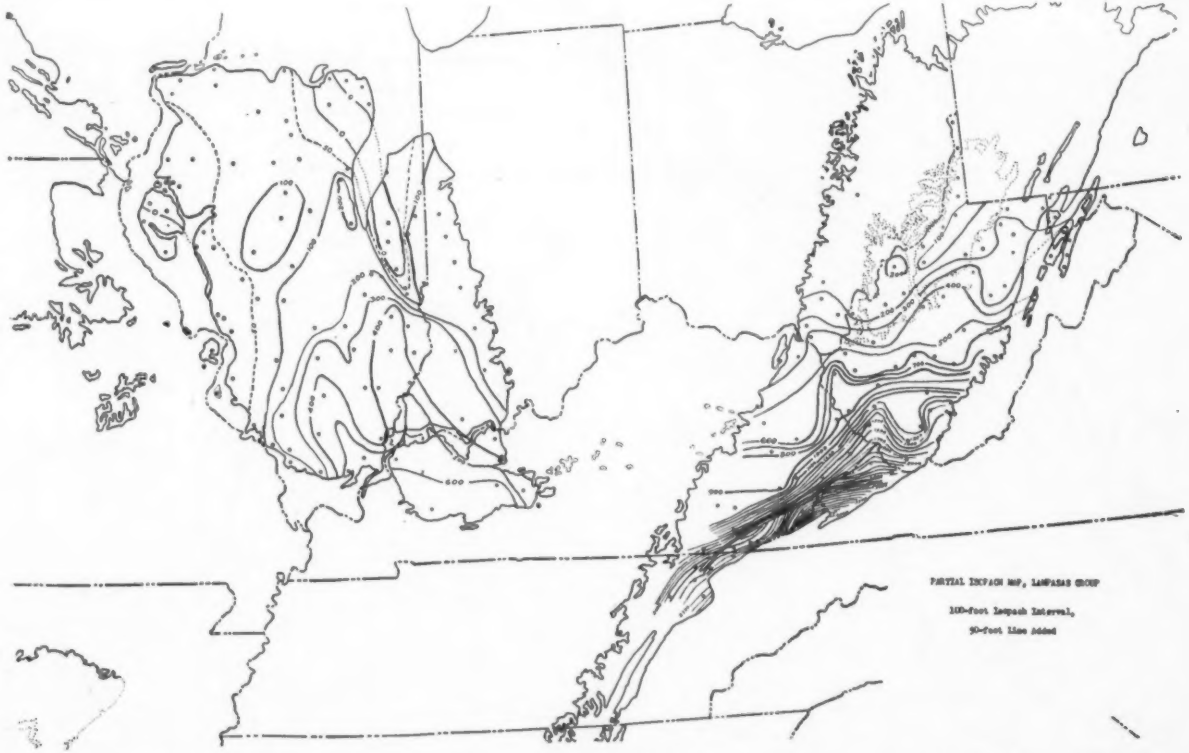


FIG. 6.—Partial isopach map of the Lampasas Group for the eastern Interior Basin and part of the Appalachian Basin. Isopach interval 100 feet.

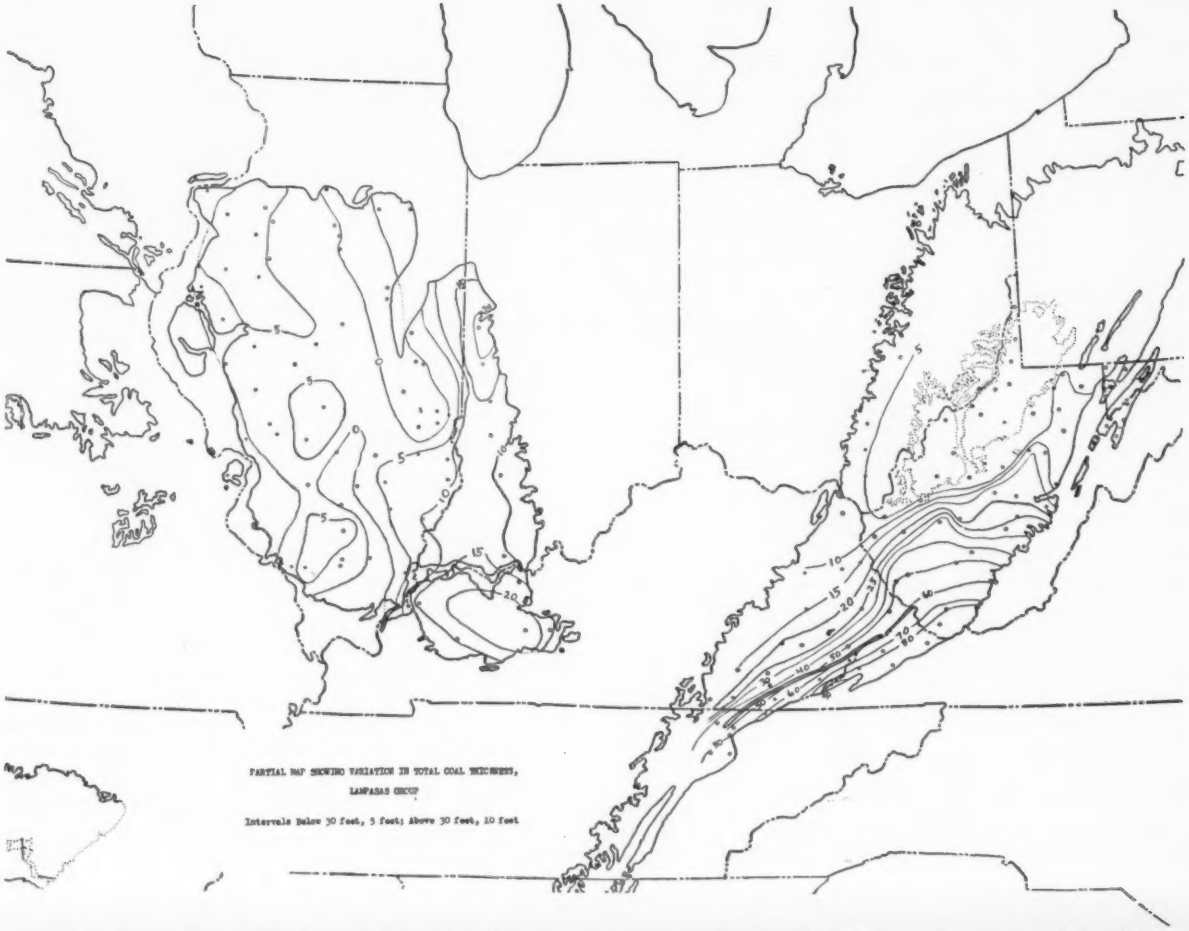

PARTIAL MAP SHOWING VARIATION IN TOTAL COAL THICKNESS,
LAMPASAS GROUP
Intervals Below 30 feet, 5 feet; Above 30 feet, 10 feet

FIG. 7.—Partial map showing variation in total coal thickness, Lampasas group. Intervals below 30 feet, 5 feet; above 30 feet, 10 feet

been devoted to the assembly of lithologic data, only two partial maps have been prepared. The first (Fig. 6) is an isopach map of the Lampasas group in parts of the Appalachian and eastern Interior basins, the boundaries used in the several states being those in the correlation chart prepared by the Pennsylvanian subcommittee of the Stratigraphic Committee of the National Research Council. This map shows a variation from zero in certain areas in Illinois, in which the earliest Pennsylvanian strata are post-Lampasas, to 4,080 feet in Lee County, Virginia, near Pennington Gap. The two areas of zero thickness are (1) along the La Salle and Oakland anticlines of eastern Illinois and (2) an area in extreme western Illinois from near Quincy southeastward toward St. Louis. In each of these areas positive tendencies, perhaps associated with post-Mississippian movements, caused the area to be sufficiently high to prevent Pennsylvanian deposition until after the Lampasas. In the eastern Interior Basin a zone of notable, though moderate, thickness, 200–300 feet, is the trough just west of the La Salle anticline. In the Appalachian field the thickness ranges from about 150 feet in southern Ohio to a maximum of 4,000 feet near the southeastern border of the field. In the southeasternmost counties this group expands southeastward at the rate of at least 100 feet per mile. The abrupt thickening on the south, as compared with the north side of the Pine Mountain thrust fault, suggests that this structure developed along a hinge line of differential downwarping which existed during Lampasas time. When data sheets have been prepared for the Ozark-Ouachita area in Arkansas and Oklahoma, it will be possible to compare the pattern of expansion there with that in Kentucky, West Virginia, and Alabama.

The only map of lithologic variation thus far prepared (Fig. 7) shows the total thickness of Lampasas coals. The coals range from zero thickness to a maximum of 91 feet, with 37 coals in Lee County, Virginia, and an aggregate of 87 feet in adjacent Wise County. In the Appalachian field the pattern of total coal-thickness variation is similar to that for the Lampasas total thickness as shown on the isopach map (Fig. 6), but there is an area in northern West Virginia with no coal, or at least less than 5 feet of coal. Although most of the source records in the several counties reporting no Lampasas coal are drillers' logs, a diamond-drill boring near Wheeling reports only 2 feet of coal and indicates that there is really very little Lampasas coal in that area. In the eastern Interior Basin the maximum coal, about 20 feet, is in the western Kentucky field, with a secondary high in the northern part of the Indiana Pennsylvanian area, where, in the Brazil Block coal field, the Minshall and Upper and Lower Block coals of Lampasas age are all minable. A map showing variation in the percentage of coal in the Lampasas group has been undertaken but is not yet completed. Another type of map, which might be useful and will be tried, is a map with a circle divided into segments to show percentages of sandstone, shale, and limestone or some other ratios of abundance of different rocks.

It is believed that numerous broadly regional relationships between variations in thickness, lithologic variation, and tectonic features will be evident as a result of further graphic studies like those suggested here. These may be considered simply preliminary samples of what may be accomplished. Lithologic-variation studies should contribute to our understanding of Pennsylvanian paleogeography, climate, and tectonic history.

FIG. 7.—Partial map showing variation in total coal thickness, Lampasas group. Intervals below 30 feet, 5 feet; above 30 feet, 10 feet

INVERTEBRATES IN PENNSYLVANIAN CORRELATIONS

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ABSTRACT

Comparatively few Pennsylvanian fossils are known to have precise zonal significance, and consequently most species at present have no more than general correlative value. This is partly because the Pennsylvanian stratigraphic sequence is uninterrupted, except locally, by important breaks separating easily distinguished faunas and partly because most Pennsylvanian species are too poorly understood to be recognized with precision and separated from closely related forms. Complications are introduced by the extreme diversity of Pennsylvanian environments, which resulted in the close stratigraphic association of almost wholly different faunules.

The faunal approach to Pennsylvanian correlation has produced results that are unsatisfactory except in a most general way. Detailed correlations can be made much more accurately on the basis of lithologic sequence, and studies of this type have revealed notable errors in correlations based on fossils. Moreover, faunal studies have resulted in the misidentification of certain diagnostic species and confusion regarding the ranges of others.

The detailed study of closely related fossils from many different stratigraphic zones in an effort to work out evolutionary trends gives great promise of much more useful and significant results. The establishment of sequences of evolutionary stages is now known to be possible and offers a means of correlation far superior to that which is dependent on the mere presence or absence of individual index species. All such studies are still in their preliminary stages, but more or less progress has been made with several groups, particularly the fusulinids.

INTRODUCTION

Some thousands of invertebrate species have been described from the Pennsylvanian rocks of America. A very few of them have precisely known stratigraphic significance, a somewhat larger number is believed to have more or less general correlative value, but the great majority is at present of little use to the careful stratigrapher.

This situation is by no means unique, although the ranges of fossils in several other systems are more completely known. Like those of other ages, many Pennsylvanian species were originally described from specimens whose exact localities and stratigraphic positions are now unknown. Old concepts regarding species were elastic, and original descriptions are generally inadequate for modern precise discrimination. These and other deficiencies are problems that have been inherited by present-day stratigraphic paleontologists.

Most other Paleozoic systems have particularly favored general localities where the succession of faunas has been worked out in more or less detail and where a considerable number of guide fossils has come to be recognized. At many of these places the stratigraphic section has obviously been interrupted, or important changes in environment have occurred, so that there are clearly marked and extensive breaks between distinctive faunas.

This is not true of the Pennsylvanian. Fossil invertebrates are rare in the type region of this system, and the intricacy of its stratigraphic details has discouraged careful zonal investigations in other areas until quite recently. Although the stratigraphic limits of a few common Pennsylvanian species have been determined, no faunal breaks comparable to those in some of the other systems have been recognized, and, with a very few more or less local exceptions, it is now

fairly certain that no such breaks exist. On the other hand, environments varied so greatly both from place to place and from time to time that almost entirely distinct faunules occur laterally in a single zone or in two adjacent beds.

At first glance this situation seems most discouraging, and undoubtedly numerous stratigraphic paleontologists, as a result, have directed their attention to other and apparently more promising fields. However, recent developments in Pennsylvanian stratigraphy, which make possible the accurate recognition and identification of many thin zones throughout wide areas, have completely changed this picture. It is now possible to assemble many collections from widely scattered localities, all precisely dated with respect to one another, in a way that cannot be duplicated in any other system. This means that assemblages of fossils can be studied and directly compared from numerous distinct successive zones arranged at reasonably short intervals throughout a very considerable thickness of strata and spanning a very considerable length of time, unbroken by any important hiatus. Thus, if evolution were progressive in any lineage, it should be possible to follow it step by step and work out certain stages indicative of definite stratigraphic zones. The recognition of such evolutionary stages would find direct application in correlations more secure than those based on the mere presence of some species and the absence of others.

PROBLEMS INVOLVED

The problems facing Pennsylvanian stratigraphic paleontologists are similar to those encountered in the study of fossils from other systems. They are of two main types: first, the establishment of already named species and, second, the recognition of constant variants, some of which may be expected to fall within well-marked evolutionary series.

It is assumed, of course, that adequate suites of specimens are available for study. These may be old collections or new, but it is absolutely essential that they be accurately located in the stratigraphic section. Exact stratigraphic position may be difficult or impossible to establish or may be more or less doubtful for old collections; hence new ones are preferable in every way. They must be carefully made in strict accordance with the most modern practices of Pennsylvanian stratigraphy, and particular care must be taken to avoid mixing of specimens from adjacent zones. Old collections of somewhat doubtful origin or new ones that for one reason or another cannot be accurately located stratigraphically are not useless, however, because they can be employed to check observations and conclusions made on other material.

FAUNAL STUDIES

The study of more or less local but complete faunas has been the method of approach to correlation by many paleontologists during the last fifty or more years, and the degree of time equivalence of different beds or formations was, and still is, believed to be indicated by the percentage of common species present in any two related faunas. This percentage method of correlation has yielded many significant and valuable results; but it is quite obvious that conditions of environment introduce complicating factors that have been considered far too little. This method may work satisfactorily in a stratigraphic province where uniform conditions were widespread and persisted for a considerable length of time or in areas where the stratigraphic section is interrupted by important breaks. Sev-

eral of the older Paleozoic systems in east-central United States meet these conditions to a greater or less extent, and correlations of their subdivisions have been made in this way with reasonable success.

The percentage method of correlation, however, fails completely in the Pennsylvanian system because of the lack of uniformity in environment. It is common knowledge that the faunules of two beds of like lithology, separated by many feet of intervening strata, are likely to contain nearly identical species, while two dissimilar adjacent beds may have almost no species in common.

Five different general types of Pennsylvanian marine faunules may be distinguished. These are: (1) characteristic limestone faunules in which molluscoidean species greatly predominate, the type of faunule with which fusulinids are commonly associated; (2) algal-limestone faunules in which mollusks predominate; (3) molluscan shale faunules; (4) black-shale faunules, also largely mulluscan, but quite different from the last. No single species occurs commonly in all five types of faunules, and many species appear to be strictly limited to faunules of one particular type.

The above rough classification is certainly arbitrary, and many intergradations occur between the faunules listed. They are all generally related to certain lithologically different, but distinctive, types of strata, and the conclusion that they were controlled by different combinations of environmental conditions can hardly be avoided. Also there are other types of faunules. Some appear abnormal because the presumably controlling factors of environment are not plainly indicated by lithology. For example, differences in salinity strongly influence the composition of a faunule, without effecting any comparable change in sedimentation.

Obviously, correlations made by the percentage method and based upon such diverse faunules can be only a source of confusion and error.

Another shortcoming of paleontological studies by faunas concerns the accurate determination of species. In his investigation of a fauna a paleontologist first sorts his specimens into groups that he considers to be species. Then he compares each group, in turn, with specimens already identified or with descriptions and illustrations in the literature. He notes the similarities and differences, and for each group he must decide whether his specimens are sufficiently similar to described forms to be referred to the same species or different enough to be considered new species or varieties. Such decisions require the exercise of sound judgment, and the conclusions reached by an experienced investigator are much more likely to stand the test of time than are those of a student without broad acquaintance with related faunas. When approached in this way, however, the conclusions of the most experienced paleontologist are open to more or less serious question on two different counts. In the first place, because he is unacquainted with the type specimens, he may be misled by imperfect or inadequate descriptions and illustrations and misidentify his specimens. Second, he is rarely able to evaluate the significance of observed minor differences and cannot be sure whether they are individual variations within a species, variations induced in response to local environmental factors, or variations that mark stages in an evolutionary series. Moreover, his misidentifications or errors in judgment are likely to be perpetuated indefinitely by later workers, even after more careful or

more complete studies have revealed their existence.

G. H. Girty's report[1] on the Wewoka fauna of Oklahoma is excellent and is probably the most useful single publication on American Pennsylvanian invertebrates. Because it is a faunal study, however, it exemplifies some of the shortcoming and faults mentioned above. For example, his specimens of *Chonetes mesolobus* do not correspond with the original description of that species based on specimens collected near St. Louis, and, consequently, he referred them to two new varieties. To indicate the differences, he illustrated and discussed specimens from Ohio that possess the characters mentioned in the original description. His conclusions were amply justified on the basis of the information available to him and to everyone else at that time. Unfortunately, however, the original description is in serious error. His specimens are comparable to the originals, and the Ohio specimens represent a distinctly different species characteristic of a different paleontologic zone in the Lower Pennsylvania.[2]

Also, the Wewoka specimens referred by Girty to *Phanerotrema grayvillensis* are not exactly similar to those occurring at the type locality, which is in a zone much higher stratigraphically. The differences are not striking, but they are constant and, once noted, easily recognized. Specimens from intermediate zones indicate that the originals and the Wewoka forms represent different stages in a single evolutionary line. Girty noted certain differences, but he was ignorant of their significance and concluded that they are unimportant. Actually, his specimens of so-called *Phanerotrema* are much more worthy of a distinctive name than either of his varieties of *C. mesolobus* because the former are characteristic of different stratigraphic zones and are useful for correlation, whereas his varieties of the latter are not.

GUIDE FOSSILS

A good guide fossil should be a common species, otherwise its absence from a faunule may have little significance. It should have been able to live under a variety of environmental conditions, so that its occurrence is not closely restricted ecologically. Also it should have short stratigraphic range. Unfortunately, there are few Pennsylvanian fossils that meet these requirements. Almost without exception, the recognized species that are common and likely to be present in various different kinds of rock were such successful and adaptable forms that they persisted for considerable lengths of time and consequently are not useful for close correlation.

Some species of this type characterize definite parts of the Pennsylvanian succession, like *Mesolobus* and several brachiopods commonly referred to *Marginifera*, which are very abundant in certain zones but also occur in smaller numbers in both higher and lower beds and whose exact stratigraphic ranges have not been accurately determined. Nevertheless, they are characteristic of several zones, such as those distinguished as series on the Pennsylvanian correlation charts;[3] but such zones are rarely sharply delimited from one another and commonly overlap. Because of these relations, however, more accurate correla-

[1] "Fauna of the Wewoka Formation of Oklahoma," *U.S. Geol. Surv. Bull. 544* (1913).

[2] J. M. Weller and R. McGehee, "Typical Form and Range of *Mesolobus mesolobus*," *Jour. Paleon.*, Vol. VII (1933), pp. 109–10.

[3] R. C. Moore and others, "Correlation of Pennsylvanian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), pp. 657–706.

tions can be made on the basis of the associations of certain common species than by noting the occurrence of any single species.

In recent years the fusulines have been studied more intensively than any other group of Pennsylvanian fossils. A considerable number of closely related genera of wide distribution and restricted stratigraphic range have been recognized by C. O. Dunbar, M. L. Thompson, and others. Although their exact ranges are still more or less incompletely known, they furnish the best means of interbasin correlation now generally available. Even when species are not identical, significant conclusions may be reached by comparing stages in the progressive development of certain structures.

Other microfossils are as yet of little value for Pennsylvanian correlations. Recent work on the ostracodes by C. L. Cooper[4] gives promise of greater usefulness for these fossils; but the smaller foraminifera and conodonts have not been sufficiently investigated for their potentialities to be known.

Sponges may be useful for local correlations in certain areas, but they are neither common enough nor widely enough distributed to be of any general importance.

The study of Pennsylvanian corals has been greatly neglected, and most specimens are commonly identified as one or another of a few old species, all of which require restudy. The work of R. M. Jeffords and R. C. Moore on Permian and Pennsylvanian corals and of W. H. Easton on Mississippian corals has shown the possibilities of modern investigations by sectioning methods; and Pennsylvanian forms offer a research field that is almost certain to produce important results.

Crinoids, although interesting and undoubtedly significant, are too rarely represented by well-preserved specimens to be of particular importance for correlation. The investigations of R. C. Moore, however, are adding greatly to knowledge of these fossils.

Bryozoans, like corals, have long been neglected. They are, however, very abundant in the Pennsylvanian at many places and exhibit a diversity of form and structure unsurpassed by any other fossils. They are now being studied by G. E. Condra and M. K. Elias and offer great promise as useful guide fossils when they are better known.

The brachiopods include more standard index fossils of the Paleozoic than any other phylum, and, until recently, brachiopods were largely relied upon for correlations in the Pennsylvanian. They are still more generally useful than any other group of fossils.

The variety of brachiopods present in the Pennsylvanian system is well indicated by the work of C. O. Dunbar and G. E. Condra.[5] They list 133 species and varieties referred to 42 genera; but they consider Lower Pennsylvanian forms incompletely. These figures are a good indication of the decline of the brachiopods after the Mississippian, in which system they are represented by more than twice as many genera and species.

Although numerous species of Pennsylvanian brachiopods are locally abundant, few of them are of general common occurrence, and most of these possess more or less elastic specific limits and range through considerable, but not sharply delimited, thicknesses of strata. Consequently, brachiopods are not at

[4] "Pennsylvanian Ostracodes of Illinois," *Ill. Geol. Surv. Bull. 70* (1946).

[5] "Brachiopoda of the Pennsylvanian System in Nebraska," *Neb. Geol. Surv. Bull. 5* (2d ser., 1932).

present particularly useful for close correlations, although they do serve admirably to mark certain general stratigraphic zones.

Dunbar and Condra's report does not indicate that they attempted to work out lines of evolutionary development in the brachiopods. Because of the very common occurrence of some forms, however, such an attempt would certainly be worth while. Unfortunately, brachiopods lack great variety in surface ornamentation and possess few other external characters, other than general shape and form, that, in combination, might distinguish significant and more or less constant varieties. The two groups that seem to offer the most promise are the chonetids and some forms generally referred to *Marginifera*.

Paleozoic pelecypods present numerous difficulties to their investigators. These arise primarily because such important features as hinge structures are rarely seen and because many forms resemble one another in shape and lack distinctive surface markings. Furthermore, the shape of certain forms varied considerably at different stages of growth. In proportion to the number of species that have been described, pelecypods are probably the most inadequately known Pennsylvanian fossils.

Pelecypods are locally very abundant in Pennsylvanian strata, but mostly they appear to have been more than ordinarily circumscribed in their habitat relations. At present they are of negligible value for correlation, but the studies of N. D. Newell indicate that detailed investigations may be expected to produce useful results in this respect.

Gastropods also were, for the most part, closely restricted in their habitats but occur locally in great abundance. Unlike the pelecypods, however, a greater proportion of the commoner forms are complexly ornamented, and they also possess a much greater potentiality for form variation than do the bivalved mollusks. Consequently, Pennsylvanian gastropods appear to offer a greater opportunity for the discrimination of stratigraphically significant varieties.

The work of J. B. Knight gives some indication of the potentialities of the gastropods, although his studies apparently were not directed toward the recognition of evolutionary series. Some of my own rather casual observations show that such series do exist among the pleurotomarids.

Cephalopods generally are neither abundant enough nor well enough preserved to be good index fossils in the Pennsylvanian. The commoner forms are nautiloids, which largely lack characters that may be used to identify closely discriminated varieties. The ammonoids, which possess much greater possibility in this regard, are mostly rare or very sporadic in their occurrence. In spite of recent studies by F. B. Plummer and Gayle Scott and by A. K. Miller and associates, the stratigraphic ranges of few species seem to be adequately known.

Trilobites are rarely even moderately abundant in the Pennsylvanian, and their remains generally occur in a dismembered condition. Recognized species and varieties also are few. Nevertheless, my studies have proved the existence of evolutionary series in the two principal genera of this age, and trilobites have been successfully used for broader correlations.

CONCLUSIONS

Investigation of the Pennsylvanian faunas of North America has lagged behind studies of the fossils of the other

Paleozoic systems. Because of this and because conspicuous faunal breaks are largely absent in the Pennsylvanian, paleontologic correlations are less precise and less certain than in several older systems. Important studies now in progress will undoubtedly furnish much better evidence for correlation than now exists, but, as long as correlations are made on a percentage basis or by the stratigraphic range-of-species method, only rather general results can be expected, which will mainly confirm rather than refine most of the correlations that are held today. On the other hand, the careful working-out of lines of evolutionary development in a reasonable number of the more common Pennsylvanian fossils is almost certain to furnish the basis for closer and more reliable interregional correlations.

Variation within evolutionary series was fairly slow, however, and there is small likelihood that paleontology can ever compete seriously with correlations based on lithologic peculiarities and the comparison of detailed stratigraphic sequences in individual basins where cyclothemic deposition occurred.

ROLE OF MICROFOSSILS IN INTERREGIONAL PENNSYLVANIAN CORRELATIONS[1]

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ABSTRACT

In the past the use of microfossils for long-distance correlations in the American Carboniferous has been somewhat restricted, largely because of the few workers interested in this class of fossils. Previous work has centered chiefly on the fusulines and ostracodes, and papers on these fossils have come mostly from the Mid-Continent region, as have also the relatively few papers on other Foraminifera and conodonts. More recent work on microfaunas from formations in the eastern Interior Basin and the West has shown that microfaunas, particularly some Foraminifera and the ostracodes, can be utilized as valuable tools in stratigraphic work.

INTRODUCTION

Three groups of microfossils, namely, the Foraminifera (particularly the fusulines), ostracodes, and conodonts have been employed in Pennsylvanian correlation studies. More than a quarter-century of work, however, has shown that the fusulines are much more useful than any of the others. In the chart and report of the National Research Council on the correlation of Pennsylvanian formations in North America[3] the fusulines are given first rank over other classes of fossils as zone markers in this system. Ostracodes have been little used in this system, largely because of the lack of sufficient work to determine diagnostic species in the several sedimentary basins. However, with the completion of three comprehensive reports—one on the Ardmore Basin, the second on the Kansas-Oklahoma area, and a third on the Illinois Basin—it is now possible to recognize a number of species that are good horizon markers. The work that has been done on Pennsylvanian conodonts has shown that, with few exceptions, the stratigraphic range of these fossils is too long for them to be useful as index fossils. This is also true of the Foraminifera other than fusulines.

Other types of microfossils, such as fragments of holothurians, echinoids, and other fossils, which include dissociated plates and other structural members, have received scant attention. Some work has been done on microcrinoids, but it is insufficient to be of stratigraphic value, except possibly at one or two horizons. Embryonic to youthful forms of the common larger fossils have been given little study or have been neglected entirely. Likewise, the Bryozoa represent, in general, a little-worked group, which probably would be of considerable stratigraphic value if more universally utilized. Some attention has also been given to sponge spicules. Finally, the diagnostic value of such things as scolecodonts, diatoms, radiolaria, molluscan radulae and opercula, and skeletal fragments of arthropods and fish is nil, largely either because of their sparse distribution or because of lack of sufficient data on which to make stratigraphic

[1] Published with permission of the chief, Illinois State Geological Survey.

[2] At the time this paper was prepared, Dr. Cooper was with the Illinois State Geological Survey.

[3] Raymond C. Moore *et al.*, "Correlation of the Pennsylvanian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), pp. 657–706 and chart.

comparisons. The use of plant material, particularly microspores, will be discussed in another paper.

FORAMINIFERA

The fusulines furnish many of the more useful fossils for the identification of Pennsylvanian formations, and the study of these forms in recent years has become a distinctly specialized branch of paleontology. Because of their structural complexity, relatively large size, and abundance in many marine zones, they make excellent guide fossils. As a result, they have been used extensively in zoning rocks of the Pennsylvanian and Permian systems, not only in North America but in many other parts of the world. A number of important papers have been published on the American Pennsylvanian forms, particularly in the Mid-Continent and contiguous areas. Many long-range correlations have been made with geologic sections outside North America, particularly those in Russia, China, and Japan—in fact, these fossils have been described from all continents.

The stratigraphic range of the Fusulinidae depends upon the classification favored. If those forms which are thought to be ancestral, such as *Endothyra*, etc., are considered true fusulines, the family extends into the Lower Mississippian or possibly even into the Upper Devonian. However, many have considered that the true fusulines are confined to the Pennsylvanian and Permian, and only recently have they been found in the Mississippian (*Millerella* of Illinois, Arkansas, and Wyoming).

The Pennsylvanian fusuline zones are based upon the predominant occurrence of the four genera, *Millerella*, *Fusulinella*, *Fusulina*, and *Triticites*. These zones overlap somewhat but correspond in the main to the groups and series of the system. Many have been further subdivided into subzones, based upon the occurrence of certain species or, in some cases, on certain genera. However, many species are geographically restricted to a single sedimentary province, having reacted to environmental conditions much as other animals do. An excellent discussion of Lower Pennsylvanian fusulines by R. C. Spivey and T. G. Roberts[4] appeared in a recent issue of the *Bulletin of the American Association of Petroleum Geologists*.

Millerella zone.—While this genus ranges from the lowest Pennsylvanian marine formations to as high as the Cisco of Texas, the *Millerella* zone has been designated by M. L. Thompson[5] as embracing those beds in which this genus occurs to the exclusion of other fusulines of the normal long-axis type. The zone is known to be well marked in Kansas, Arkansas, Oklahoma, Texas, New Mexico,[6] Utah, and Colorado;[7] and, no doubt, further work will show it to be present in other areas where marine rocks of Springer (Morrow) age are developed.

Fusulinella zone.—This genus characterizes the section above the Springer, containing beds of Atoka and lowest Des Moines age. It is present in the Pottsville (Mercer) limestones of Ohio, the Upper Marble Falls of Texas, the Tradewater

[4] "Lower Pennsylvanian Terminology in Central Texas," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXX (1946), pp. 181–86.

[5] "Pennsylvanian Morrowan Rock and Fusulinids of Kansas," *Kan. Geol. Surv. Bull. 52*, Part VII (1944), pp. 409–31, Pls. 1, 2, Figs. 1, 2.

[6] M. L. Thompson, "Pennsylvanian System in New Mexico," *N.M. School of Mines Bull. 17* (1942).

[7] M. L. Thompson, "Pennsylvanian Rocks and Fusulinids of East Utah and Northwest Colorado Correlated with Kansas Section," *Kan. Geol. Surv. Bull. 60*, Part II (1945), pp. 17–84, Pls. 1–6, Figs. 1–11.

(Seville) of Illinois, and the lowermost Des Moines of Iowa. A lower subzone, characterized by *Profusulinella* (or *Fusiella* of Lee), and an upper zone, the *Fusulinella iowensis* subzone, are present. Only recently the suggestion has been made that a group of closely related species of *Fusulinella*,[8] which are characteristic of pre–Des Moines beds, be considered the "zone of *Fusulinella*," even though younger species are associated with *Wedekindellina* in higher zones.[9] Other genera commonly found associated with *Fusulinella* are *Millerella*, *Pseudostaffella*, and *Eoschubertella*.

Fusulina zone.—This zone, immediately above the *Fusulinella* zone, delineates all the Des Moines not included in the lower zone. Its upper boundary, the Des Moines–Missouri line, is the position of the most significant faunal break in the Pennsylvanian, not only for the fusulines but for many other classes of fossils as well. Although *Fusulina* is found with *Fusulinella* in the lowest Des Moines, it does not occur above the upper boundary of this series. Subzones are marked by *Wedekindellina* in the lower part and *Fusulina girtyi* and *F. exima* in the upper Des Moines. These zones are well marked in the Mid-Continent, Rocky Mountain, and central Interior basins. Only the upper subzone is known in Ohio, *Wedekindellina* apparently being absent there.[10]

Triticites zone.—Just as *Fusulina* is confined to beds below the Des Moines–Missouri boundary, *Triticites* is not found in the formations below the Missouri series of the Upper Pennsylvanian. However, it continues upward into the Lower Permian (Wolfcamp series). The zone is widespread in North America, and three zones, characterized by *T. irregularis*, *T. cullomensis*, and *T. ventricosus*, are recognized. In the lower zone *T. irregularis* is similar to *T. ohioensis* and appears to occur at about the horizon of the Kansas City group. Other genera, such as *Millerella*, *Schubertella*, *Waeringella*, and *Dunbarinella* make up only minor parts of the fusuline faunas of the Upper Pennsylvanian.[11] An excellent bibliography and systematic review of genera was published by Dunbar and Henbest.[12]

The smaller Foraminifera have not furnished horizon markers in the same proportion as have the fusulines. This is partly due to the lack of extensive work on these forms, but it is, in the main, due to the long range of most of the known genera and species, again reflecting the reappearance of like forms with the repetition of similar environmental conditions. Mrs. Plummer[13] has found, after her extensive work on the Texas section, that "most of the species have such long vertical ranges that they are of little value in this depositional province. Faunal assemblages apparently follow facies, and, with no major breaks in the sequence, faunas in general are repeated with repetition of facies in the column." In writing about the Marble Falls Foraminifera, she says:

> In this thick and almost consistently calcareous Marble Falls formation, a thin incidental noncalcareous and sandy layer is characterized wholly by the same forms that are so highly characteristic of superjacent noncalcareous and silty to sandy formations, and it emphasizes forcibly the need to study faunal groups in close association with obvious field

[8] Thompson, p. 29 of ftn. 6.

[9] Spivey and Roberts, pp. 182–85 of ftn. 4.

[10] Carl O. Dunbar and Lloyd G. Henbest, "Pennsylvanian Fusulinidae of Illinois," *Ill. Geol. Surv. Bull. 67* (1942), p. 30.

[11] Thompson, p. 42 of ftn. 7.

[12] Ftn. 10.

[13] Personal communication.

TABLE 1*

SUMMARY FAUNAL CHART SHOWING FORAMINIFERA FROM LOWER PENNSYLVANIAN OF TEXAS

SPECIES	Marble Falls	Smithwick	Strawn	Unrestricted
Proteonina cervicifera Cushman and Waters				x
Thurammina texana Cushman and Waters				x
Thuramminoides sphaeroidalis, n. sp.				x
Hyperammina bulbosa Cushman and Waters				x
Hyperammina clavacoidea, n. sp.				x
Hyperammina elegantissima, n. sp.				x
Hyperammina spinescens Cushman and Waters				x
Hyperamminoides expansus, n. sp.				x
Earlandia minuta (Cushman and Waters)				x
Reophax arenatus (Cushman and Waters)			x	
Reophax asper Cushman and Waters				x
Reophax bendensis, n. sp.	x			
Reophax emaciatus, n. sp.				x
Reophax expatiatus, n. sp.			x	
Reophax fittsi (Warthin)				x
Reophax glennensis (Harlton)				x
Reophax minutissimus, n. sp.				x
Reophax tumidulus, n. sp.			x	
Ammodiscus semiconstrictus Waters				x
Glomospira compressa Waters		x		
Glomospira articulosa, n. sp.				x
Glomospirella umbilicata (Cushman and Waters)				x
Haplophragmoides confragosus, n. sp.				x
Ammobaculites minutus Waters				x
Ammobaculites stenomecus Cushman and Waters				x
Endothyra distensa, n. sp.	x			
Endothyra rotaliformis Warthin	x			
Endothyra whitesidei Galloway and Ryniker				x
Endothyranella armstrongi sobrina, n. subsp.	x			
Bradyina holdenvillensis Harlton	x			
Bradyina sp.	x			
Bigenerina perexigua, n. sp	x			
Cribrostomum marblense, n. sp.	x			
Cornuspira sp.	x			
Calcitornella sp.	x			
Trepeilopsis sp.	x			
Globivalvulina sp.	x			
Mooreinella biserialis Cushman and Waters				x
Polytaxis scutella (Cushman and Waters)	x			

*After Helen J. Plummer (see ftn. 14).

relationships and with lithology of the enclosing strata, in order not to be misled by species.[14]

The available literature is very limited in scope and is published for the most part under the names of a small number of workers—namely, J. A. Cushman and J. A. Waters,[15] J. J. Galloway and B. H. Harlton,[16] J. J. Galloway and Charles Rynicker,[17] B. H. Harlton,[18] Helen J. Plummer,[19] Robert Roth and John Skinner,[20] A. S. Warthin,[21] and J. A. Waters.[22] Therefore, it is not possible, at the present state of our knowledge, to make comparisons between the smaller foraminiferal faunas of the various sedimentary basins of North America. My own information on the Illinois Pennsylvanian does not permit conclusions that are in any way different from those reached by Mrs. Plummer from her study of the Texas section.

Of the previously described species shown in Table 1, five have been found restricted to a single formation, three to the Marble Falls, and one each to the Smithwick and Strawn. In her analysis of the Texas faunas, Mrs. Plummer reports the new species *Hyperammina elegantissima*, *Reophax emaciatus*, *R. expatiatus*, and *R. tumidulus* as good markers for the Strawn, and *R. bendensis* for the Marble Falls. No restricted species were listed from the Smithwick, all species ranging upward into the Strawn.

OSTRACODES

There is a considerable volume of literature on the Pennsylvanian ostracodes of North America, consisting mostly of short papers on faunas that are very limited stratigraphically. In order to obtain a comprehensive stratigraphic summary it is necessary to examine this extensive literature describing many hundreds of species from scores of localities and formations, principally from the Mid-Continent and adjacent areas. The most important papers are by H. H. Bradfield,[23]

[14] Helen Jeanne Plummer, "Smaller Foraminifera in the Marble Falls, Smithwick, and Lower Strawn Strata around the Llano Uplift in Texas," *Tex. Univ. Pub. 4401* (1945), p. 215.

[15] "Pennsylvanian Foraminifera from Michigan," *Contr. Cushman Lab. Foram. Res.*, Vol. III (1927), pp. 107–10, Pl. 22; "Arenaceous Paleozoic Foraminifera from Texas," *ibid.*, pp. 146–53, Pls. 26, 27; "The Development of *Climacammina* and Its Allies in the Pennsylvanian of Texas," *Jour. Paleon.*, Vol. II (1928), pp. 119–30, Pls. 17–20; "Some Foraminifera from the Pennsylvanian and Permian of Texas," *Contr. Cushman Lab. Foram. Res.*, Vol. IV (1928), pp. 31–35, Pls. 4–7; "Additional Cisco Foraminifera from Texas," *ibid.*, pp. 62–67, Pl. 8; "Upper Paleozoic Foraminifera from Texas," *Jour. Paleon.*, Vol. II (1928), pp. 358–71, Pls. 47–49; "Foraminifera from the Cisco Group of Texas," *Tex. Univ. Pub. 3019* (1930), pp. 22–81, Pls. 2–12.

[16] "Some Pennsylvanian Foraminifera of Oklahoma, with Special Reference to the Genus *Orobias*," *Jour. Paleon.*, Vol. II (1928), pp. 338–57, Pls. 45, 46; "*Endothyranella*, a Genus of Carboniferous Foraminifera," *ibid.*, Vol. IV (1930), pp. 24–28.

[17] "Foraminifera from the Atoka Formation of Oklahoma," *Okla. Geol. Surv. Circ. 21* (1930).

[18] "Some Pennsylvanian Foraminifera of the Glenn Formation of Southern Oklahoma," *Jour. Paleon.*, Vol. I (1927), pp. 15–27, Pls. 1–5; "Pennsylvanian Foraminifera of Oklahoma and Texas," *ibid.*, pp. 305–10, Pls. 52, 53; "Micropaleontology of the Pennsylvanian Johns Valley Shale of the Ouachita Mountains, Oklahoma, and Its Relationship to the Mississippian Caney Shale," *ibid.*, Vol. VII (1933), pp. 3–29, Pls. 1–7.

[19] "Calcareous Foraminifera in the Brownwood Shale near Bridgeport, Texas," *Tex. Univ. Pub. 3019* (1930), pp. 1–21, Pl. 1.

[20] "The Fauna of the McCoy Formation, Pennsylvanian, of Colorado," *Jour. Paleon.*, Vol. IV (1930), pp. 332–52, Pls. 28–31.

[21] "Micropaleontology of the Wetumka, Wewoka, and Holdenville Formations," *Okla. Geol. Surv. Bull. 53* (1930).

[22] "A Group of Foraminifera from the Dornick Hills Formation of the Ardmore Basin (Oklahoma)," *Jour. Paleon.*, Vol. I (1927), pp. 129–33, Pl. 22; "A Group of Foraminifera from the Canyon Division of the Pennsylvanian Formations in Texas," *ibid.*, Vol. I (1928), pp. 271–75, Pl. 42.

[23] "Pennsylvanian Ostracoda of the Ardmore Basin, Oklahoma," *Bull. Amer. Paleon.*, Vol. XXII, No. 73 (1935).

Coryell *et al.*,[24] B. H. Harlton,[25] W. R. Johnson,[26] and Betty Kellett.[27] Of these, two stand out because of their comprehensive study of ostracodes from a large stratigraphic section. Bradfield's report on the ostracodes of the Ardmore Basin, Oklahoma, describes the fauna from all the Pennsylvanian overlying the Springer formation. This section embraces some 3,000 feet or more of beds in the Dornick Hills, Deese, and Hoxbar groups, which range in age from Morrow to the top of the Missouri series. Kellett's reports involve the Pennsylvanian and Permian section of Oklahoma and Kansas and give the stratigraphic distribution of species in formations ranging from the base of the Missouri to the top of the Big Blue (Permian) series. The two reports overlap, in that each describes ostracodes from the Missouri series.

An analysis of the range of Paleozoic ostracode genera made a few years ago[28] showed that over half the Mississippian genera did not continue into the Pennsylvanian. In this category might be mentioned a few characteristic genera which are present in the Chester, such as *Bairdiolites*, *Carboprimitia*, *Chesterella*, *Denisonella*, *Graphiodactylis*, and *Perprimitia*. A like portion of the Pennsylvanian genera originate in the Mississippian or earlier, and, of these, about two-thirds continue into the Permian.

The results of my own studies on the Pennsylvanian of Illinois[29] give the ostracode faunas from zones ranging in age from Morrow to the top of the Virgil, representing the entire Mid-Continent section, except for some horizons present west of the Mississippi that are missing or unfossiliferous in Illinois. An analysis of all the available data shows that, when the total number of species is considered, comparatively few species are good horizon markers.

[24] H. N. Coryell, "Some New Pennsylvanian Ostracoda," *Jour. Paleon.*, Vol. II (1928), pp. 87–94, Pl. 11, pp. 377–79, Pl. 51; H. N. Coryell and G. A. Osorio, "Pennsylvanian Ostracoda, and Ostracode Fauna from the Nowata Shale," *Amer. Mid. Nat.*, Vol. XIII (1932), pp. 25–40, Pl. 5; H. N. Coryell and Gladys D. Billings, "Pennsylvanian Ostracoda of the Wayland Shale of Texas," *Amer. Mid. Nat.*, Vol. XIII (1932), pp. 170–89; H. N. Coryell and C. H. Sample, "Pennsylvanian Ostracoda: A Study of the Ostracode Fauna of the East Mountain Shale, Mineral Wells Formation, Texas," *Amer. Mid. Nat.*, Vol. XIII (1932), pp. 245–81, Pls. 24–26; H. N. Coryell and R. T. Booth, "Pennsylvanian Ostracoda: A Continuation of the Ostracoda Fauna from the Wayland Shale, Graham, Texas," *Amer. Mid. Nat.*, Vol. XIV (1933), pp. 258–78, Pls. 3–5.

[25] "Some Pennsylvanian Ostracoda of the Glenn and Hoxbar Formations of Southern Oklahoma and the Upper Part of the Cisco Formation of Northern Texas," *Jour. Paleon.*, Vol. I (1927), pp. 203–12, Pls. 32, 33; "Pennsylvanian Ostracodes from Oklahoma and Texas," *ibid.*, Vol. II (1928), pp. 132–41, Pl. 21; "Pennsylvanian Ostracoda from Menard County, Texas," *Tex. Univ. Pub. 2901* (1929), pp. 139–61, Pls. 1–4; "Some Upper Mississippian (Fayetteville) and Lower Pennsylvanian (Wapanucka-Morrow) Ostracoda of Oklahoma and Arkansas," *Amer. Jour. Sci.*, Vol. XVIII, No. 105 (5th ser., 1929), pp. 254–70, Pls. 1, 2; see also ftn. 18 (1933).

[26] "The Ostracoda of the Missouri Series in Nebraska," *Neb. Geol. Surv. Paper 11* (1936), pp. 1–52, Pls. 1–5.

[27] "The Ostracode Genus *Hollinella:* Expansion of the Genus and Description of Some Carboniferous Species," *Jour. Paleon.*, Vol. III (1929), pp. 196–217, Pls. 25–26; "Ostracodes of the Upper Pennsylvanian and Lower Permian Strata of Kansas. I. The Aparchitidae, Beyrichiidae, Glyptopleuridae, Kloedenellidae, Kirkbyidae, and Youngiellidae," *ibid.*, Vol. VII (1933), pp. 59–108, Pls. 13–16; "Ostrocodes from the Upper Pennsylvanian and Lower Permian Strata of Kansas. II. The Genus *Bairdia*," *ibid.*, Vol. VIII (1934), pp. 108–38, Pls. 14–19; "Ostracodes of the Upper Pennsylvanian and Lower Permian Strata of Kansas. III. Bairdiidae (*concl.*), Cytherellidae, Cyprinidae, Entomochonchidae, Cytheridae, and Cypridae," *ibid.*, Vol. IX (1935), pp. 132–66, Pls. 16–18; "Carboniferous Ostracodes," *ibid.*, Vol. X (1936), pp. 769–84.

[28] Chalmer L. Cooper, "Occurrence and Stratigraphic Distribution of Paleozoic Ostracodes," *Jour. Paleon.*, Vol. XVI, No. 6 (1942), pp. 764–76.

[29] "Pennsylvanian Ostracodes of Illinois," *Ill. Geol. Surv. Bull. 70* (1946).

AGE	APPALACHIANS		MIDCONTINENT AND CENTRAL INTERIOR BASIN								
	SER.	FLORAL ZONES	SER.	GROUPS	BRACHIOPODS	AMMONITES	CRINOIDS	FUSULINES ZONE	FUSULINES SUBZONE	OSTRACODES	CONODONTS
PERMIAN	DUNKARD	Callipteris	WOLFCAMP	ADMIRE		Perrinites		Schwagerina	S. emaciata S. huecoensis	Kellettina robusta	
PENNSYLVANIAN	MONONGAHELA	Odontopteris Danaeites Lescuropteris	VIRGIL	WABAUNSEE SHAWNEE DOUGLAS	Lissochonetes, Chonetes transversalis	Uddenites	Delocrinus vulgatus	Triticites	T. ventricosus T cullomensis	Bairdia concava Hollinella moorei	Streptognathodus elongatus Prioniodus? conflexus
	CONEMAUGH	Pecopteris Neuropteris flexuosa	MISSOURI	PEDEE LANSING KANSAS CITY BRONSON BOURBON	Chonetina	Eothallaoceras Prouddenites	Apographiocrinus typicalis			Hollinella radlerae Bairdiacypris deloi Bairdia spinosa	Gondolella spp
	ALLEGHENY	Neuropteris rarinervis	DES MOINES	MARMATON CHEROKEE	Mesolobus mesolobus Marginifera muricatina	Owenoceras Wellerites	Delocrinus granulosus Plaxocrinus mooresi	Fusulina	F. exima F. girtyi Wedekindellina	Silenites lenticularis Cavellina equalis	Gondolella magna G. cruvata Idiognathus acutus
	KANAWHA	Neuropteris tenuifolia Cannophyllites	TI VALLEY	ATOKA	Marginifera nana M. hystericensis Mesolobus striatus	Paralegoceras		Fusulinella	F. iowensis	Bairdia ardmorensis	Streptognathodus n. sp.
	LEE	Mariopteris pygmaea M. pottsvillea Anemites N. pocahontas M. eremopteroides		MORROW (Springer)	Marginifera nana M. hystericensis Hustedia miseri	Gastrioceras Brannerоceras	Stereobranchi-crinus	Millerella	Profusulinella M. marblensis M. inflecta	Polytylites wapanuckensis	Polygnathus wapanuckensis Streptognathodus ouachitensis
MISS.	MAUCH CHUNK	Rhodea goepperti	CHESTER		Composita subquadrata	Eumorphoceras	Proterocrinus	Millerella spp.		Bairdiolites Carboprimitia	Cavusgnathus cristata

* In par. after Moore *et al.*, 1944.

Ti Valley series.—This name is suggested in the Illinois report as a solution for the Morrow-Atoka-Lampasas–Marble Falls nomenclatural problem and includes the Morrow and Atoka groups, the latter being used with the stratigraphic connotation of Spivey and Roberts.[30] The series is characterized by *Ectodemites harltoni*, from the Johns Valley shale and the Ferdinand of southern Indiana, and *Kirkbya bendensis*, from the same zones. The lower part of the series, the Morrow, contains the distinctive *Polytylites wapanuckensis* as well as *Monoceratina ardmorensis*. In the Atoka group the lower Ferdinand formation contains *Bairdia ardmorensis* and *Ectodemites plummeri* from the Dornick Hills and Marble Falls, respectively. The next higher formation, the Seville, does not have the restricted species common to zones in the Mid-Continent, but several new species appear to be restricted in the Illinois Basin.

Des Moines series.—In the Mid-Continent and Illinois Basin areas this series provides a number of species common to both groups and formations. *Cavellina equalis* is found in the lowest group, the Cherokee, and *Coryellites cooki* is characteristic of the Liverpool and upper Deese.

The Marmaton group contains *Geisina gregaria*, *Microparaparchites brazoensis*, and *Silenites lenticularis*. The Summum contains *Healdiacypris perplexa* from the upper Deese and the Brereton, while *Geisina gallowayi*, *Jonesina dubia*, and *Bairdia citriformis* are from comparable horizons in the west. The position of the Lonsdale near the top of the Des Moines is indicated by such species as *Cavellina cavellinoides*, *C. lintris*, *Hollinella nowataensis*, *Jonesina deesensis*, and *Microparaparchites cuneatus*. The next higher formation, the Exline, contains *Cavellina jejuna*, *Healdia formosa*, and *Jonesina trisulcata*.

Missouri series.—*Kirkbya arcuata* marks this series, but no species are known to be restricted to the oldest group, the Bronson. The Kansas City is indicated by *Bairdiacypris deloi* and *Jonesina infrequens*. In the Lansing group the La Salle–Livingston-Millersville zone is characterized by *Hollinella radlerae*, *Bairdia hooverae*, *B. lunata*, *Ectodemites sullivanensis*, and *Bairdiacypris haydenbranchensis*, the first three from the upper Missouri of the Mid-Continent and the other two from Indiana.

Virgil series.—The Virgil contains *Bairdia scholli* and *Cavellina laevis*, which also are found in the upper formations of the Illinois section. The Shawnee Little Vermilion formation contains *Healdia masoni* and *Knightina ampla*, while the Newton-Shumway zone has *Bairdia pinnula*, *Cavellina nebrascensis*, *Healdia coryelli*, *Hollinella moorei*, and *Silenites silenus*. The youngest Illinois formation, the Woodbury, is marked by *Ectodemites edsonae*, present in the Hoxbar of Oklahoma, somewhat lower in the section. Kellett's work has shown that "almost all of the Permian ostracode genera are found also in late Pennsylvanian strata, and with few exceptions, the same genera predominate. Many of the common species in earliest Permian faunas are Pennsylvanian survivals, but in addition a dozen new species occur. By mid-Permian (Leonard) time few Pennsylvanian species survived, although a number of close relatives may be recognized. In general mid-Permian ostracodes are more highly ornamented than Pennsylvanian species, especially in the families Kirkbyidae and Kloedenellidae."[31]

[30] P. 185 of ftn. 4; see also Cooper, ftn. 30.

[31] Personal communication.

CONODONTS

Conodonts, so numerous and varied in the Upper Devonian and Lower Mississippian, while still rather plentiful in the Upper Mississippian and Pennsylvanian, are represented by few genera and species in the younger system. They are quite numerous in the black shales, which have furnished the many assemblages that have been described. The literature contains comparatively few papers on Pennsylvanian conodonts, the principal workers being Samuel Ellison,[32] F. H. Gunnell,[33] and C. R. Stauffer and Helen J. Plummer.[34] Like many other classes of fossils, conodonts are creatures of environment and so, like many other Pennsylvanian forms, are largely of long stratigraphic range. The most important stratigraphic and taxonomic study[35] shows that nearly all species lived throughout Pennsylvanian times. One species, *Cavusgnathus giganta*, apparently started in the Chester and lived on into the Permian. Very little is known about conodonts from the Upper Mississippian or from those formations classed as "Mississippian and/or Pennsylvanian." As in other transition zones, genera from both systems are found, such as *Cavusgnathus*, *Gnathodus*, and *Metalonchodina*. The following details of the fauna and the chart are summarized from Ellison's report:[36] Species of *Prioniodus*, *Ligonodina*, *Lonchodina*, *Hibbardella*, *Prioniodina*, *Synprioniodina*, *Ozarkodina*, *Spathodus*, and *Hindeodella* are present throughout the system, some being restricted, many extending into the Permian.

Ti Valley series.—The only described fauna from this series is that of Harlton,[37] and this contains only three species. Two features distinguish this series, namely, *Polygnathodella* is known only from the Morrow, and *Gondodella* is not known to range below the base of the Des Moines.

Des Moines series.—The most important feature of this series is the presence of large numbers of idiognathodids, but the only restricted species is *Idiognathodus acutus*. *Gnathodus* and *Metalonchodina* are also rather abundant and are not known in younger formations. While *Gondodella* is not common, *G. curvata* and *G. magna* are characteristic of several zones within the Marmaton.

Missouri series.—Most striking is the abundance of idiognathodids, streptognathodids, and gondodellids: *I. lobatus*, *Streptognathodus sulcatus*, *S. concentricus*, and *S. oppletus* are confined to the series. There is a noticeable disappearance of many idiognathodids near the top of the Missouri. *Gondodella dubia* is confined to the Hushpuckney member of the Swope formation, and *G. symmetrica* to the Stark shale member of the Dennis, both in the Bourbon group. Two species of *Cavusgnathus*—*C. lauta* and *C. flexa*—begin in the Missouri but carry on into the Permian.

Virgil series. — Streptognathodids, mostly *S. elegantulus*, make up over three-fourths of the Virgil fauna. Here *S. elegantulus* and *Prioniodus conflexus* appear for the first time and continue

[32] "Revision of Pennsylvanian Conodonts," *Jour. Paleon.*, Vol. XV (1941), pp. 107–43, Pls. 20–23; "Conodonts as Paleozoic Guide Fossils," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXX, No. 1 (1946), 93–110.

[33] "Conodonts from the Fort Scott Limestone of Missouri," *Jour. Paleon.*, Vol. V (1931), pp. 244–52, Pl. 29.

[34] "Texas Pennsylvanian Conodonts and Their Stratigraphic Relations," *Tex. Univ. Bull. 3201* (1932), pp. 13–50.

[35] Ellison, ftn. 33 (1941).

[36] *Ibid.*, pp. 108–11, Fig. 4.

[37] See ftn. 18 (1933).

into the Big Blue series. All gondodellids except *Gondodella denuda* and *G. elegantula* disappear in zones above the lower Virgil Lecompton formation.

This analysis of conodont faunas pertains to the Pennsylvanian of Missouri and Kansas. There are no comparable faunal data covering other sedimentary basins. Outside of a few papers on Oklahoma formations by Harlton[38] and by R. W. Harris and R. V. Hollingsworth,[39] the only other comprehensive Pennsylvanian conodont paper is by Stauffer and Plummer[40] on the Texas Pennsylvanian. My own observation is that there is little variation in conodont faunas throughout the whole system or from one sedimentary basin to another. They seem to follow ecological conditions closely, and faunas are found to be repeated numerous times under the multiple repetition of similar beds during this system. The few possibilities for guide fossils are the platform types, which have furnished the small number of restricted forms that are now known. Even these may possibly be shown to have considerable range by future work. More reports like that by Ellison are needed for other areas.

[38] *Ibid.*

[39] "New Pennsylvanian Conodonts from Oklahoma," *Amer. Jour. Sci.*, Vol. XXV (5th ser., 1933), pp. 193–204, Pl. 1.

[40] See ftn. 34.

PENNSYLVANIAN FLORAL ZONES AND FLORAL PROVINCES[1]

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ABSTRACT

Paleontologic correlation must be guided by principles, some of which are stated here, derived from a study of living organisms and their distribution. In application of these principles, nine floral zones in the Arcto-Carboniferous province of Pennsylvanian floras are considered. The floras included are all lowland, warm-climate, rain forest assemblages. In the Rocky Mountain area certain floral types appear that are thought to represent upland floras. In the Antarcto-Carboniferous province the Pennsylvanian floras differ greatly in the main and are believed to represent coal-climate, rain forest assemblages. A few representatives of these assemblages are considered, and a few Arcto-Carboniferous elements present are regarded as immigrants during an epoch of milder climate.

INTRODUCTION

The following statement, written in connection with a discussion of Devonian faunas over forty years ago, requires only slight modification to make it applicable to land floras. It contains, in fact, many of the fundamental ideas of sound stratigraphic paleontology. The import of these remarks has frequently been lost sight of but is of great consequence.

Students of geographical distribution have shown that in distant parts of the same ocean the species are widely divergent, as much difference existing between the marine faunas of the southern and northern temperate zones as between the faunas of the successive formations of a continuous geological section. It is evident from this observation that discussions of the time relations of fossils must treat not only of the genetic affinity of the forms making up a fauna, but of the geographic distribution and of the geological range of the species concerned.[2]

As a basis for the ensuing presentation of paleontologic data, it is pertinent to introduce several of the principles of the science that are of value in the study of Paleozoic floras. Their statement may recall them to more active use, with beneficial results, and it is with this purpose that they are set down.

First is the biological principle that forms the fundamental basis for paleontologic work: The facts and accepted hypotheses of modern biology, although not always applicable, are the bases for studies of fossil organisms. The features of modern classifications that are proved to be of importance must be the elements of any classification of fossils. It is generally recognized that the paleontologist, owing to imperfect preservation of the remains with which he works, must accept, as his primary bases for determining identity and relationship, superficial characteristics that are deemed of secondary importance in the classification of most living organisms. This fact he should fully admit, and he should recognize that, in consequence, superficial homeomorphy may be wrongly interpreted and that many patterns of "evolutionary trends" may be more apparent than real. In short, the paleontologist must be fully aware, and be prepared to admit, that interpretations of generic and even specific relationships of fossil organisms are based on opinion rather

[1] Published by permission of the director, U.S. Geological Survey.

[2] H. S. Williams, "The Correlation of Geological Faunas," *U.S. Geol. Surv. Bull. 210* (1903), p. 15.

than on the biologic details that permit the student of living organisms to determine affinity.

Several ecological and geographical principles are of considerable importance in stratigraphic work. They are, briefly, as follows:

1. *The fundamental unit in ecologic and geographic studies is the biota or life-association.*—The biota is also fundamental in geologic work. Since the paleontologist rarely has recourse to the complete association, he should accept the largest and most representative sample available. Should he choose to make a special study of only a part of the sample, such as a family or a genus, he should admit this limitation by qualification of his results.

2. *Organisms are rarely cosmopolitan.*—There are very few known forms so adaptable that they have a general or universal distribution on continental masses.

3. *Associations living during a limited period of time in the same general region are much more alike in their constitution and the proportionate abundance of dominant species than are those of widely separated regions.*—In this principle we find a justification for the method of correlation in restricted areas through abundance of certain species in a stratal zone and an explanation of the common failure of such a zone to maintain its identity over wide areas. We likewise find an explanation of variation in fossil content in widely separated areas of strata that we believe to be contemporaneous.

4. *The association of elements of one flora with those of another suggests an intermediate environment if, on other bases, the floras are known to represent different habitats.*—If they are considered to represent similar or identical habitats, such floras are indicative of different stratigraphic positions, or they may be from some intermediate region that marks the general position of a path of intercommunication or migration.

5. *Variations in content of associations may be due to geographic distribution or geological range.*

6. *Widespread distribution of organisms or associations is to be expected in a negligible period of time only when there is adequate evidence that the areas occupied are equally and broadly continuous. If the areas occupied are recognized as discontinuous, it is then to be expected that the geologic time involved will be variable but not always negligible.*

7. *Identical genera or species may frequently be traced through several life-associations that form a geographic or a geologic succession or both. Accepting correlation by the use of associations, the oldest occurrence of a species or genus suggests the approximate locus of its origin.*

8. *Of paramount importance in geographic and geologic work is the recognition of the facts that* (a) *practically simultaneous changes in forms often occur over areas of great geographic spread and* (b) *more protracted changes in forms occur in a small area during appreciable intervals of geologic time.*—These changes may develop uniformly, or they may take place in surges. Stratigraphic variation in species, genera, or biotas may be explained by migration, changes, or hiatuses. A hiatus can be recognized, on paleontologic grounds, with certainty and properly evaluated only when the suspected local absence of a biota can be proved through its presence elsewhere in the region.

Further, I wish to present three opinions concerning associations of Pennsylvanian floras:

1. Floras of the Pennsylvanian coal swamps of the Northern Hemisphere

have many morphological characteristics that suggest that they persisted under conditions no cooler than those of present-day, warm-temperate rain forests.

2. Floras of the Pennsylvanian equivalents in the Southern Hemisphere originated under conditions no warmer than, and possibly similar to, the cool-temperate rain forests or provinces of the present day.

3. Upland floras are believed to have existed during much, if not all, of the period of existence of land plants. Their remains are not likely to be preserved in the fossil record because of distance of habitats from basins of deposition. They may be expected in the sedimentary record if local conditions were such that basins occurred adjacent to uplands.

FLORAS OF PENNSYLVANIAN AGE

Two major floral provinces have been recognized as existing during the Pennsylvanian epoch: (1) the northern or Arcto-Carboniferous province of warm-climate, rain forest coal floras and (2) the southern or Antarcto-Carboniferous province of cool-climate, rain forest floras.

ARCTO-CARBONIFEROUS FLORAS

STANDARD SEQUENCE OF PENNSYLVANIAN FLORAS

The study of Pennsylvanian fossil plants has been largely a study of the "Coal Measures" floras, groups of plants that occur in strata that are largely continental in origin and that are believed to have accumulated in extensive flood plains and in deltas under mild and humid climatic conditions. Nine successive floral zones are recognized in the eastern and Mid-Continent regions of North America. These zones provide a practical basis for general correlation of the containing rocks, "general correlation" not implying the precise establishment of boundaries of the floral zones. Obviously, in thick sequences of clastic strata the possibility of preservation everywhere of characteristic floras at the precise position of their extinction is unlikely. The stratigrapher can, therefore, only "rough in" the stratigraphic units through strict paleontologic work.

Secondary floral characteristics, such as relative abundance of certain species, may be further used for detailed local correlations, but only rarely are they valuable over large areas. Preferred for refinements of correlation within floral zones when possible are field mapping and direct tracing.

The nine floral zones have been named from characteristic genera or species. Such naming of zones does not mean, however, that knowledge of the index or marker fossils alone is sufficient for recognition. The names given are those of certain more common forms; but definite zone identification requires a study of the entire flora when possible. The nine zones and their gross distribution are given in Table 1. The following paragraphs discuss these zones in greater detail.

Zone 1.—Zone of *Neuropteris pocahontas* and *Mariopteris eremopteroides*. This zone is recognized as characteristic of the lower Lykins coals of the Pottsville formation in the Anthracite fields of Pennsylvania and of the Pocahontas formation in West Virginia. It is likewise identifiable in the southern Appalachians in areas of expansion of the Pottsville formation. Throughout much of the area the limits of the zone have not been clearly established. Correlative units probably exist in many parts of the United States but are rarely of facies suitable for preservation of fossil plants.

Zone 2.—Zone of *Mariopteris pottsvillea* and of common occurrence of *Aneimites* spp. Floras belonging to this

zone occur in Lykins coal No. 4, in the lower part of the New River formation of West Virginia, and at traceable positions farther south. Such floras also occur locally at the base of the Pennsylvanian series in the Mid-Continent region. Thus the Wayside member of the Caseyville formation, southern Illinois, carries this association.

TABLE 1

Zone	Name	Appalachian Region	Mid-Continent Region
9.....	*Danaeites*	Upper part of Monongahela formation	In Mid-Continent region Zones 8 and 9 are not separable and could together be designated the zone of *Odontopteris* spp.
8.....	*Lescuropteris*	Lower part of Monongahela formation and upper part of Conemaugh formation	
7.....	*Neuropteris flexuosa*, and *Pecopteris* spp.	Upper part of Allegheny formation	Upper part of Des Moines group
6.....	*N. rarinervis*	Lower part of Allegheny formation	Lower part of Des Moines group
5.....	*N. tenuifolia*	Major portion of Kanawha formation	Major portion of Lampasas group
4.....	*Cannophyllites*	Base of Kanawha formation	Base of Lampasas group
3.....	*Mariopteris pygmaea*, *Neuropteris tennesseeana*, *Ovopteris communis*, *Alloiopteris inaequilateralis*, and *Alethopteris decurrens*	Coals 2 and 3 of the type Pottsville formation, upper part of New River formation, upper part of Lee formation	Morrow formation
2.....	*Mariopteris pottsvillea* and *Aneimites* spp.	Lykins coal No. 4 of Pottsville formation, lower part of New River formation	Base of Pennsylvanian series in Mid-Continent region
1.....	*Neuropteris pocahontas* and *Mariopteris eremopteroides*	Lower Lykins coals of Pottsville formation and Pocahontas formation	

Zone 3.—Zone of *Neuropteris tennesseeana*, *Ovopteris communis*, *Alloiopteris inaequilateralis*, *Alethopteris decurrens*, and *Mariopteris pygmaea*. As indicated by its contained floras, this zone is widespread in the Appalachian region and in the Mid-Continent area. It occurs in the roofs of coal Nos. 2 and 3 of the type Pottsville, is characteristic of the upper part of the New River formation in West Virginia, and is found in the upper part of the Lee formation farther south. It is likewise known from the Morrow formation and its equivalents in the Mid-Continent region.

The following list of selected plants has been made to illustrate a characteristic flora of this zone. Drurey shale (Battery Rock member), NW. $\frac{1}{4}$ sec. 32, T. 10 S., R. 1 W., Carbondale Quadrangle, Illinois: *Pecopteris serrulata*, *Alethopteris lonchitica*, *A. decurrens*, *A. owenii*, *A. owenii* var. *grandifolia*, *A. owenii* var. *helenae*, *A.* sp., *Neuropteris tennesseeana*, *Neuropteris* spp., *Linopteris* sp., *Mariopteris pygmaea*, *M. speciosa*, *Mariopteris* spp., *Diplothmema cheathami*, *Diplothmema* sp., *Eremopteris inaequilateralis*, *Cardiocarpon* spp., *Cordaites principalis*,

Sphenophyllum sp. cf. *S. longifolium, S. cuneifolium, Lepidophyllum campbelleanum, Sigillariostrobus* spp.

Zone 4.—Zone of common occurrence of *Cannophyllites*. This zone may be recognized at or near the base of the Kanawha formation and its equivalents in the Appalachian region and at the base of the Lampasas group in the mid-continent region. It is frequently difficult to identify because of similarities of many of its elements to those of adjacent strata.

The following list has been compiled from several collections in western Illinois and illustrates the general characteristics of floras assigned to this zone. Tarter member, Tradewater formation in (1) SW. ¼ SW. ¼ sec. 27, T. 11 S., R. 4 E., Marian Quadrangle, Illinois; (2) NE. ¼ SW. ¼ SW. ¼ sec. 29, T. 12 N., R. 2 W., Monmouth Quadrangle, Illinois; (3) NE. ¼ NE. ¼ sec. 36, T. 9 N., R. 1 W., Avon Quadrangle, Illinois; (4) vicinity of Port Byron, Illinois: *Pecopteris serrulata* (2), *Neuropteris tenuifolia* (early form) (1), *Archaeopteris stricta* (1), *Cannophyllites marginata* (4), *Cannophyllites abbreviata* (4), *C. dawsoni* (1), *C. rectinervis* (2), *C. southwelli* (3, 4), *C. fasciculata* (4), *Alethopteris* sp., *Eremopteris grandis* (2), *Ovopteris communis* (2), *Cardiocarpon* sp. (large) (2, 3), *Trigonocarpus* sp. (2), *Sigillaria rugosa* (2), *Annularia cuspidata* (2), *Lepidodendron aculeatum* (3).

Zone 5.—Zone of *N. tenuifolia*. This zone is characteristic of the major portion of the Kanawha formation and is apparently also characteristic of rocks included in the Lampasas group in the Mid-Continent region.

The following list of species from the shale above the Cannelton coal at Tell City, Indiana, illustrates a typical flora from this zone: *Alethopteris lonchitica, A. owenii, N. scheuchzeri, N. tenuifolia, Mariopteris* sp., *Cardiocarpon* sp., *Trigonocarpum* sp., *Lepidodendron* sp., *Lepidophyllum* sp., *Lepidostrobus* sp.

Zone 6.—Zone of *N. rarinervis*. The flora, characterized by *N. rarinervis*, occurs in the lower part of the Allegheny formation in the Appalachian region and in the lower part of the Des Moines group in the Mid-Continent region. It is the highest zone in the suite of Lower Pennsylvanian floras.

The following floras, collected from the roof of the Murphysboro coal at mines near Murphysboro, Illinois, is characteristic of this zone: *Pecopteris vestita, Alethopteris serlii, Mariopteris occidentalis, M. sillimanni, Neuropteris ovata, N. scheuchzeri, N. rarinervis, N. clarksoni, Linopteris rubella, Odontopteris* sp., *Cordaites communis, Lepidophyllum oblongifolium, Stigmaria ficoides, Calamites suckowi, Annularia stellata, Sphenophyllum emarginatum.*

Zone 7.—Zone of *N. flexuosa* and appearance of abundant *Pecopteris* spp. This zone occurs in the upper part of the Allegheny formation and is characteristic of the upper part of the Des Moines group. It is the lowest zone in the suite of Upper Pennsylvanian floras.

Zones 8 and 9.—Zones of *Lescuropteris* and *Danaeites*, respectively. These two zones are separable in the Appalachian region, where the lower, Zone 9, characterizes the upper Conemaugh and lower Monongahela formations. The upper, Zone 8, is characteristic of the upper part of the Monongahela formation. In the Mid-Continent region the two cannot everywhere be separated and perhaps should be designated as a single unit—the zone of *Odontopteris* spp.

The following list, compiled from collections from the Chanute shale, Kansas City group, illustrates a flora from the lower part of the *Odontopteris* zone:

Mariopteris pluckenetii, M. cordato-ovata, Sphenopteris pinnatifida, Aloiopteris winslovii, Alethopteris virginiana, Alethopteris sp. cf. *A. virginiana, A. grandini, Odontopteris reichiana, Neuropteris ovata, N. plicata, N. scheuchzeri, Annularia stellata, Sphenophyllum oblongifolium, Sigillaria camptotaenia.*

FLORAL MODIFICATIONS IN THE ROCKY MOUNTAIN REGION

With this brief sketch of the characteristic floral sequence in the typical Pennsylvanian series, it is now appropriate to examine the floras of rock sequences some distance from Coal Measures deposition. In the southern Rocky Mountains considerable stratigraphic work involving the Pennsylvanian series has been undertaken in recent years. Physical conditions and sedimentation in that area were unlike those of the coal basins. A series of linear positive elements, developed in early Pennsylvanian time, and variable quantities of continental and marine sediments were deposited in the adjacent basins. Certain of the positive areas were sufficiently large to provide considerable tracts of uplands.

Remains of plants that are occasionally found in the clastic portions of the Pennsylvanian sequences afford an opportunity for comparison with floras in the Appalachian and Mid-Continent areas. Since these floras are still in process of investigation, I shall draw from them only a few illustrations bearing on an important point.

In the Weber(?) formation of the Mosquito Range, in central Colorado, a flora belonging to Zone 3, the zone of *Mariopteris pygmaea*, has been described.[3]

[3] C. B. Read, "A Flora of Pottsville Age from the Mosquito Range, Colo.," *U.S. Geol. Surv. Prof. Paper 185* (1934), pp. 79–96.

At a locality in the lower 100–200 feet of the formation on Evans Peak, the following species were found: *Neuropteris dluhoschi, N. heterophylla, N. gigantea?, Sphenopteris hoeningshausii, Sphenopteris* sp. cf. *S. microcarpa, Diplothmema cheathami, D. patentissima, Adiantites rockymountanus, Cordaites* sp., *Cordaicarpon* sp., *Trichopitys whitei, Dactylophyllum johnsoni, Lepidostrobus weberensis, Stigmaria verrucosa, Calamites* sp., *Asterophyllites longifolius*(?). The dominant species are those of the Coal Measures facies. Fernlike plants and representatives of the Cordaitales are abundant, and remains of Lycopodiales are rare. There are also present, in abundance, the putative conifers *Trichopitys* and *Dactylophyllum.*

In the Upper Pennsylvanian strata of the McCoy formation, north-central Colorado, occur fernlike plants associated with species of the Paleozoic conifer, *Walchia.* The following florule is reported from interval 74, McCoy formation near Yarmony School, Eagle County, Colorado: *Odontopteris mccoyensis, Samaropsis hesperius, Walchia stricta, Walchia* sp., *Walchiastrobus* sp.[4] The flora appears to belong to Zone 7, the zone of *N. flexuosa,* and is therefore, in terms of the typical Pennsylvanian section, equivalent to the flora in the upper part of the Allegheny formation.

In northern New Mexico the Sandia formation and the lower part of the superjacent Madera limestone contain fairly typical Coal Measures floras in which fernlike plants and *Cordaites* sp. are dominant. In the upper part of the Madera limestone floras containing *Walchia* spp. and other conifers occur.

[4] C. A. Arnold, "Some Paleozoic Plants from Central Colorado and Their Stratigraphic Significance," *Univ. Mich., Contr. Mus. Paleon.,* Vol. VI (1941), pp. 59–70.

From these notes on the Pennsylvanian floras of the Rocky Mountain region an important conclusion may be drawn. The plant associations, in the older parts of the Pennsylvanian sequences, are similar to those of the Coal Measures but, through the relative rarity of Lycopodiales, suggest a drier habitat than that indicated by the approximately contemporaneous floras in the eastern coal basins. The higher Pennsylvanian floras are striking departures from the plant associations of the same general ages, in the eastern coal basins, as inferred from index forms and independent stratigraphic data. These plants in the western area occur in suites of sediments that were deposited during a period of widespread orogeny in the southern Rocky Mountains. During this period of mountain-building many geologic data indicate a restriction of lowland and an expansion of upland habitats or areas. The floral modifications are in the direction of mesophytic associations.

For the modifications that occur in the Rocky Mountains I propose that the term "Cordilleran flora" be used.

ANTARCTO-CARBONIFEROUS FLORAS

Upper Carboniferous floras of the Southern Hemisphere contrast strikingly with those of the Arcto-Carboniferous province. An outline of the sequence and distribution of the continental Upper Carboniferous deposits is, however, not within the scope of this paper, and it is therefore sufficient to call attention only to the general features of a few representative sequences.[5]

In Argentina the Pagonzo system includes strata of Lower Carboniferous, Upper Carboniferous, Permian, and Triassic ages. Tillites occupy the basal portions of the sequence and appear to be of Lower Carboniferous and early Upper Carboniferous ages. Above are continental deposits of various types, and still higher are some marine beds.

In Brazil the Santa Catherina system is essentially identical with the Pagonzo system of Argentina. It has been divided into the Itararé, Tubarão, and Passa Dois series, which, in turn, have been divided into local units. The Itararé series is a sequence of tillite and interbedded shale and sandstone and is conformably overlain by the Tubarão series, which is the principal coal-bearing unit in the Paraná Basin.

From the lowest part of Stage 1 of the Pagonzo system, floras of probable Chester or late Mississippian age are reported. Succeeding them are associations characterized by an abundance of *Glossopteris* spp., *Gangamopteris* sp., and *Phyllotheca* sp. A similar flora is known from the Itararé tillite in southern Brazil. Itararé series, Paraná Basin, Brazil (1) near Suspiro, Rio Grande do Sul; (2) Teixeira Soares, Paraná: *Gangamopteris obovata* (1), *Glossopteris indica*, *Gl. browniana*, *Gl.* sp., *Phyllotheca* sp., *Brachyphyllum* sp. cf. *B. australe*.

In the upper part of Stage 1 of the Pagonzo system as well as from the Tubarão series in Brazil occur floras that contain, in addition to species of *Glossopteris* and *Phyllotheca*, an abundance of *Pecopteris*, *Zeilleria*, *Annularia*, *Sphenophyllum*, and *Lepidodendron*. Illustrative of the association, the following forms from a single locality are listed: Tubarão series, Cambuhy, Rio das Pedras, Paraná, Brazil;[6] *Pecopteris pedrasica* (Ar),

[5] C. B. Read, "Plantas fósseis do Neo-Paleozóico do Paraná e Santa Catarina," *Brasil, Min. Agr., Dept. Nac. Prod. Min., Div. Geol. Min., Mono. 12* (1941), pp. 1–102.

[6] In the list forms indicated by "I" are known by the writer to occur in the Itararé series. Forms indicated by "An" are considered typical members

P. cambuhyensis (Ar), *P. paranaensis* (Ar), *Zeilleria oliveirai* (Ar), *Glossopteris indica* (I, An), *Glossopteris* sp. (I, An), *Glossopteris* sp. cf. *ampla* (I, An), *Sphenophyllum oblongifolium* (Ar), *Annularia? americana* (Ar), *Phyllotheca australis* (I, An), *Phyllotheca* sp. (I, An), *Brachyphyllum* sp. cf. *B. australe* (I), *Buriadia* sp. (An), *Lepidostrobus* sp. (Ar, An), *Lepidodendron pedroanum* (Ar, An).

A preliminary conclusion is that such floras as those from the upper part of Stage 1, Pagonzo system, and from the Tubarão series, Santa Catherina system, are correlative with the upper part of the Pennsylvanian series of North America. This conclusion is based on the general similarity of the types common in the floras. It is further concluded that the tillite sequence which contains a zone of abundant *Glossopteris*, *Gangamopteris*, and *Phyllotheca* is also of Pennsylvanian age.[7]

The presence of a flora so dissimilar to those known in the Arcto-Carboniferous province, succeeded by others having many similarities to Arcto-Carboniferous floras, is perhaps explained by reference to the rock sequences. The floras of the Itararé series and its equivalents are in shale interbedded with tillite. The environment, although probably not then glacial in the area inhabited by the plant associations, was probably more rigorous than is generally characteristic of Carboniferous floras. It is apparent from a consideration of paleogeography that the Antarcto-Carboniferous area in question was separated from Arcto-Carboniferous land areas; therefore, opportunities for development of dissimilar floras were present. Following maximum glaciation in the Pennsylvanian of South America, climatic amelioration occurred, as indicated by the presence of coal in the superjacent rocks. During, or prior to, that period of time, members of the Arcto-Carboniferous floras presumably migrated into the Southern Hemisphere and became common in the known plant associations.

of the Antarcto-Carboniferous flora; by "Ar" are those related closely to Arcto-Carboniferous types. Several of these are conspecific with, or closely related to, forms that occur in the Arcto-Carboniferous floras of the Pennsylvanian series.

[7] Read, ftn. 5.

SUMMARY

Two major floral provinces have been recognized as existing during the Pennsylvanian epoch: (1) the northern or Arcto-Carboniferous warm, rain forest province of coal floras and (2) the southern or Antarcto-Carboniferous cool, rain forest province. In the Arcto-Carboniferous province the dominant associations preserved are Coal Measures floras. The eastern and Mid-Continent regions appear to have been a rather continuous lowland, across which shallow seas intermittently advanced and retreated, and physical conditions must have been generally similar everywhere in the basin. Thus widespread migration of plant associations in negligible time is probable, and the floral zones may be inferred to have chronologic value.

In portions of the Rocky Mountain region there were restricted lowlands and basins of deposition adjacent to rapidly rising geanticlines. Modifications of the lowland floras are found there, these modifications being due to the inclusion of mesophytic forms. The presence of such types may be explained by the existence of upland habitats, with mesophytic floras growing upon them, adjacent to sites of deposition; it may also be interpreted in terms of regional climatic variations.

To the sequence of rain forest lowland or Coal Measures floras the term "Arcto-

Carboniferous" has been applied because of the widespread occurrence of this suite of associations in the Pennsylvanian or Upper Carboniferous rocks of the Northern Hemisphere. For the modifications that occur in the southern Rocky Mountains the term "Cordilleran flora" is recommended.

The Antarcto-Carboniferous floras were, during earlier Pennsylvanian time, dominantly cool, rain forest types that developed independently or semi-independently of the Arcto-Carboniferous floras. During later Pennsylvanian time there was sufficient migration of Arcto-Carboniferous floras southward to modify the earlier existing floras. This occurred at a time of climatic amelioration following glaciation.

More important than the discussion of these wanderings of the Pennsylvanian floras are the principles that have been suggested. Geographical distribution is a frequently neglected factor in studies of Paleozoic organisms. Furthermore, differences between floras on the two margins of a single major depositional area are sufficiently great to require the utmost care in establishing even approximate correlations. Such care consists of weighing all available evidence, organic and stratigraphic, and of study of entire associations rather than of certain selected biologic groups.

It is perhaps inadvisable to draw any generalization from these observations. Depending upon one's point of view, it might be concluded that land floras show so many variations that regional correlations based on them are of doubtful value. Equally possible is the conclusion that problems of geographical distribution and variation have not been sufficiently considered by paleontologists.

PLANT MICROFOSSILS IN CORRELATION OF COAL BEDS[1]

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ABSTRACT

An intensive study of fossil microspores, isospores, and prepollens isolated from Illinois coal beds has proved that numerous genera and species are present. The correlation of coal beds is possible because the geological range of many genera and species is proved, by this investigation, to be quite restricted.

Preliminary experiments with specific interregional correlations have demonstrated a wide lateral distribution of plant microfossils necessary for the correlations of this type.

INTRODUCTION

The purpose of this paper is to show that plant microfossils may be used effectively in the correlation of spore-bearing strata. The extent to which they may be used interregionally is of utmost importance if rapid progress is to be made in stratigraphic studies. These preliminary results will therefore help to evaluate the role which plant microfossils can play in interregional correlations. A final report will include descriptions of the many new genera and species of plant microfossils isolated from Illinois coal beds and the methods of isolating them for study.

Although plant spores were observed in coal more than a hundred years ago, it is only recently that these microscopic remains have been used by European geologists in solving stràtigraphic problems. Their use is practically unknown in this country. This is readily understood by paleobotanists familiar with the numerous taxonomic problems which they present. A recent publication[2] has considerably lessened the taxonomic problems, so that investigators may now place plant spores in their appropriate genera. The present investigation is the first comprehensive survey of isolated microspores, isospores, and prepollens of Paleozoic strata in this country. J. M. Schopf,[3] using megaspores, indicated their possible use in correlating coal beds. The first correlation studies of two Ohio coal beds based on isolated small spores proved successful.[4]

DISTRIBUTION OF SMALL-SPORE GENERA IN ILLINOIS COAL BEDS

THE CASEYVILLE GROUP

The oldest Pennsylvanian strata in Illinois contain ten established genera and at least three new genera. *Densosporites* and *Lycospora* are the dominant genera, and thus in all probability the coals of this group were largely derived from the parent-plants of these two genera. The parent-plant of *Densosporites* is unknown, but certainly the spores of *Lycospora* are those of the arborescent lepidodendrons.

The Wayside, Battery Rock, and

[1] Published with the permission of the chief, Illinois Geological Survey, Urbana, Illinois.

[2] J. M. Schopf, L. R. Wilson, and Ray Bentall, "An Annotated Synopsis of Paleozoic Fossil Spores and the Definition of Generic Groups," *Ill. Geol. Surv. Rept. Investigations No. 91* (1944), pp. 1–66.

[3] "Spores Characteristic of Illinois Coal No. 6," *Trans. Ill. Acad. Sci.*, Vol. XXVIII, No. 2 (1936), pp. 173–76; "Spores from Herrin (No. 6) Coal Bed in Illinois," *Ill. Geol. Surv. Rept. Investigations No. 50* (1938), pp. 1–73.

[4] R. M. Kosanke, "The Characteristic Plant Microfossils of the Pittsburgh and Pomeroy Coals of Ohio," *Amer. Mid. Nat.*, Vol. I (1943), pp. 119–32.

Reynoldsburg coal beds from southern Illinois are considered to be of Caseyville age, which is in agreement with J. M. Weller, L. G. Henbest, and C. O. Dunbar.[5] The coal beds of the Caseyville group appear to lack species of the genus *Cirratriradites*, and the genus *Laevigato-sporites* may have originated in Reynoldsburg time. At least, *Laevigato-sporites* is represented in the Caseyville by only a few specimens, which is surprising, because spores of this type are known to have an almost continuous range from the Pennsylvanian to the present day.[6] If *Laevigato-sporites* originated in Reynoldsburg time, there must have been a major floral change. Such a floral change supports the correlation[7] of the Babylon coal bed as post-Caseyville, because the genus is abundantly represented in the Babylon coal bed, as is the genus *Cirratriradites*. The Babylon coal bed was formerly considered to be Caseyville.[8]

THE TRADEWATER GROUP

The Tradewater group contains species of fourteen established genera and at least two new genera which are present in the Caseyville group. The flora was more diversified, and the dominant genus throughout most of this period was *Laevigato-sporites*, which was scantily represented earlier. Only *Lycospora* replaces *Laevigato-sporites* as the dominant floral element in one coal bed. The subdominant genera during part of this time are *Granulati-sporites*, *Cirratriradites*, *Triquitrites*, and *Lycospora*. In most cases each of the momentary periods of subdominance indicates the origin of new species, which serve as guide fossils. Also *Alati-sporites*, *Cirratriradites*, *Florinites*, and possibly *Reinschospora* appear for the first time during the Pennsylvanian period in Illinois.

The Willis and Tartar, Pope Creek and Delwood, Seville and Rock Island coal beds are to be correlated on the basis of plant microfossils, which is in agreement with C. L. Cooper.[9] The Curlew coal bed is thought to be younger than the Rock Island and Seville coal beds,[10] and this view is held by the author. The Bald Hill coal bed, originally described by G. H. Cady,[11] is younger than the Curlew coal bed. The Davis and Wiley are correlated and likewise the DeKoven and Greenbush; this is in agreement with Wanless' suggested correlations.[12]

THE CARBONDALE GROUP

The coal beds of the Carbondale group present fewer correlation problems than any other group in Illinois. One new genus is of utmost importance in correlating the No. 2 coal bed and is known to occur only in the lower half of the bed. This coal bed has species of *Lycospora* as the dominant microfloral element; and a species of *Laevigato-sporites*, with its origin in the DeKoven coal bed,

[5] "Pennsylvanian Fusulinidae of Illinois," *Ill. Geol. Surv. Bull. No. 67* (1942), pp. 9–34.

[6] L. R. Wilson and R. M. Webster, "Plant Microfossils from a Fort Union Coal of Montana," *Amer. Jour. Bot.*, Vol. XXXIII, No. 4 (April, 1946), pp. 271–78; Olof H. Selling, "Spores of Hawaiian Pteridophytes. I." *Spec. Pub. 37, Bishop Museum, Honolulu, Hawaii* (Göteborg, Sweden, 1946), pp. 1–87.

[7] R. C. Moore, H. R. Wanless, J. M. Weller, *et al.*, "Correlation of Pennsylvanian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944), pp. 657–706.

[8] Weller, Henbest, and Dunbar, ftn. 5; Harold R. Wanless, "Pennsylvanian Correlation in the Eastern Interior and Appalachian Coal Fields," *Geol. Soc. Amer. Spec. Paper 17* (1939), pp. 85 and 108.

[9] "Pennsylvanian Ostracodes of Illinois," *Ill. Geol. Surv. Bull. 70* (1946), p. 16.

[10] C. O. Dunbar and L. G. Henbest, "Pennsylvanian Fusulinidae of Illinois," *Ill. Geol. Surv. Bull. 67* (1942), pp. 20–21.

[11] "The Areal Geology of Saline County," *Trans. Ill. Acad. Sci.*, Vol. XIX (1926), pp. 259–60.

[12] Ftn. 8 (1939).

becomes a prominent member of the flora. Number 5 coal bed is readily distinguished by an abundance of *Laevigatosporites*, fewer *Lycospora*, and the presence of several species of *Alati-sporites* and *Cirratriradites*. Number 5-A coal bed is distinct from both No. 5 and No. 6 coal beds. It does not correlate with the Grape Creek coal bed, which is in contrast to the correlations of J. M. Weller and H. R. Wanless[13] and of Wanless.[14] The correlation of the Grape Creek coal bed with No. 6 coal bed by F. H. Bradley[15] is upheld by spore studies in which no generic or specific differences have been noted. The Grape Creek coal bed has been variously correlated as No. 5 coal bed[16] and No. 5-A coal bed.[17] The large spores of No. 6 coal bed, megaspores, are known through the works of J. M. Schopf.[18]

THE McLEANSBORO GROUP

In the McLeansboro group there are more stratigraphic problems than in any other group in Illinois. Much additional work must be done before the problems can be solved. However, there are fourteen established genera known to occur and at least one new genus is present. Changes in the distribution and abundance of genera are most encouraging. Danville No. 7 coal bed is definitely younger than the Jamestown or Bankston Fork coal beds. It may be identical with the Cutler coal bed or the first Cutler rider coal bed. There exists a major floral break just below No. 8 coal, indicated by the fact that no species of *Lycospora* has as yet been observed in No. 8 coal. This is the approximate position of the boundary of the Des Moines and Missouri series of the Mid-Continent, according to Cooper.[19] Coal samples from type areas of the Shoal Creek and Carlinville show that they do not correlate and that they are separate and distinct strata. Further, they show that the Carlinville is probably older than the Shoal Creek. The presence of the genus *Pityosporites* in the Shoal Creek and younger beds strongly suggests the presence of an upland conifer flora.

SUMMARY OF SMALL-SPORE INVESTIGATIONS IN ILLINOIS

These remarks are based on more than six hundred macerations from forty-seven counties in the state. A study of Figure 1 readily reveals that, through a knowledge of the genera and their abundance, one can place an unknown coal bed in one of the four groups of the Pennsylvanian system, and in many cases even identify it specifically. A knowledge of the numerous species and their abundance readily permits the correlation of Pennsylvanian spore-bearing strata in Illinois.

PRELIMINARY INTERREGIONAL CORRELATIONS

After a comprehensive survey of the spore content of Illinois coal beds had been made, it was important to investigate the possibility of using plant remains isolated from spore-bearing strata

[13] "Correlation of Minable Coals of Illinois, Indiana, and Western Kentucky," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIII, No. 9 (1939), pp. 1374–92; reprinted in *Ill. Geol. Surv. Circ. No. 48* (1939).

[14] Pp. 84 and 110 of ftn. 8.

[15] "Geology of Vermilion County," *Ill. Geol. Surv.*, Vol. IV (1870), pp. 241–65.

[16] H. R. Wanless, quoted in G. H. Cady, "Classification and Selection of Illinois Coals," *Ill. Geol. Surv. Bull. 62* (1935), p. 39.

[17] Weller and Wanless, ftn. 13; and Wanless, ftn. 8.

[18] Ftn. 3.

[19] Ftn. 9.

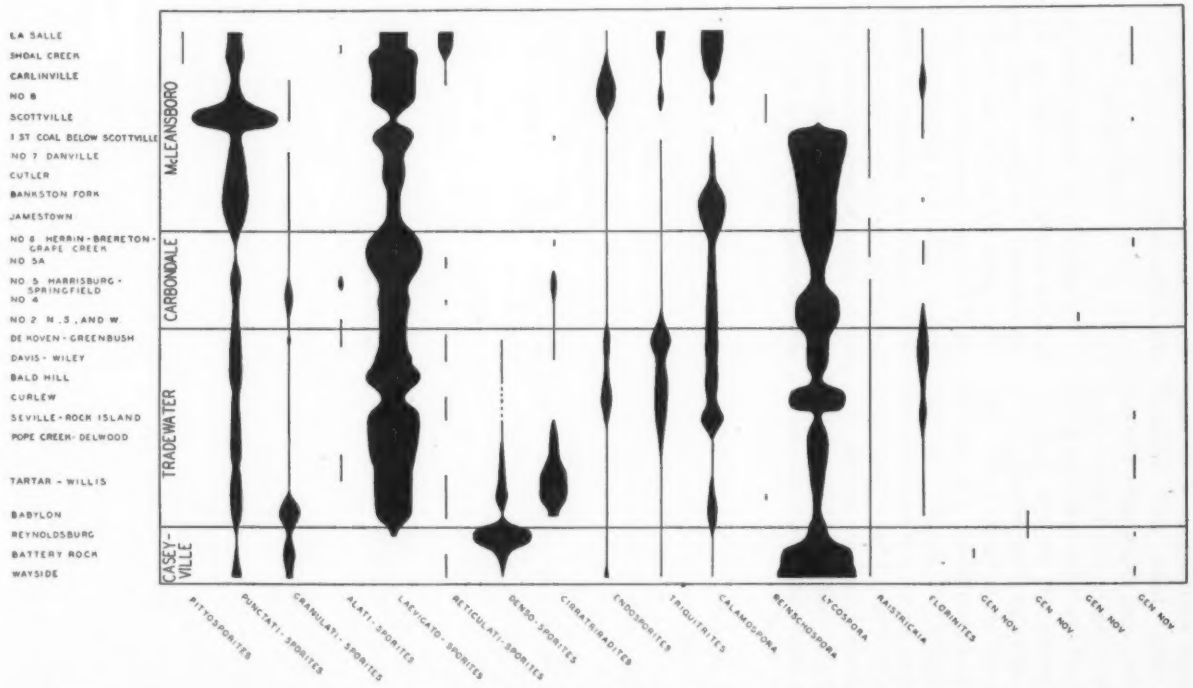

FIG. 1.—Distribution and relative abundance of the small-spore genera in a number of Illinois coal beds. The coal beds are listed to the left and the genera at the base. The genus *Punctati-sporites* for the Wayside coal bed represents 10 per cent, and this may be used as a scale.

for interregional correlations. Coal samples from Ohio, Iowa, and Missouri were prepared and examined. The results are encouraging and may be summarized as follows: Characteristic plant spores are present in the coal beds investigated, although their abundance is thought to be at variance with comparable horizons in Illinois. This may be due to ecological conditions. The preliminary tests suggested possible correlations with certain Illinois beds, but, because of limited samples, specific correlations should not be made at this time. Microfloral zones, known from Illinois coal beds, may be used to correlate interregionally.

CONCLUSIONS

Correlation of Pennsylvanian spore-bearing strata is possible by the use of microspores, isospores, and prepollens when prepared by the maceration method. This type of research gives promise of being a useful tool to the geologist and is of importance to the paleobotanist in determining the range and abundance of fossil plants. Numerous investigations of this kind should be carried out in critical areas throughout the country.

SPORE FLORAS OF THE PENNSYLVANIAN OF WEST VIRGINIA AND KENTUCKY

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ABSTRACT

Each of nearly one hundred coal seams of Pennsylvanian age has been sampled at several localities in West Virginia and adjacent states. Maceration residues of these coal samples show a differentiation of the microfossil flora between the seams, which may represent evolutionary or/and ecological changes. Preliminary studies have been made on the megaspores which permit some advance conclusions. Sixty species and varieties of the megaspore flora of twenty selected seams are illustrated and discussed. Fifteen types of microspores from three seams are given from among fifty-eight recognized in all the coals studied. The principal floral changes appear to occur above the Lower War Eagle and Buffalo Creek coals and below the Uniontown coal. Less important changes are noted above the Matewan, Cedar Grove, and Lower Kittanning coals. Some evidence for interregional correlation based on similar geologic occurrence of certain spores is given. Several problems of the morphology and identification of spores are presented in the illustrated discussion of spore characteristics.

INTRODUCTION

The investigation of the microfossils of the Pennsylvanian coal seams of a portion of the Appalachian coal field has been under way since August, 1940. The principal study has been devoted to the coals of the Kanawha (Upper Pottsville) and Lower Allegheny series of southern West Virginia and eastern Kentucky. Since circumstances during these years have hindered the work, this paper must be understood as a report of progress. The researches in hand may be divided into several projects, each of which will be published as it is completed. The objectives were stated before an earlier meeting of geologists[1] and need not be reviewed here. The project which deals with the identification and classification of the microfossil assemblages is in itself a complex problem. The procedure and progress of this study to date are briefly presented.

COLLECTIONS

Early field work was limited to collecting samples of coal from mines in economically important coal seams, whose advertised identifications were presumed to be correct. Before work had proceeded far it was found that these identifications were too unreliable for a detailed study. All subsequent collections, over 750 samples from the area shown in Figure 1, were made from horizons which could be determined with reasonable accuracy by established methods of correlation. The geographic distribution of the samples thus far examined is also shown in Figure 1. Locality numbers given there are not those on the filed samples but, instead, are arbitrary designations for convenience in this report. At Localities Nos. 1–23, 28, 31–35, and 39, individual collections from particular coal seams were made. Numbers 24–27, 30, 36–38, and 40 refer to localities where thick series of exposed strata include a number of coal seams. Locality No. 29 includes three complete sections taken from three closely spaced drill cores. Several hundred additional collections awaiting further examination are not indicated on this figure.

Figure 2 shows the geologic distribution of some of the coals sampled and

[1] American Association for the Advancement of Science, Geology Section, Cleveland, 1944.

FIG. 1.—County outline map of most of West Virginia and adjacent areas of Kentucky, Ohio, and Pennsylvania, showing localities (Nos. 1–40) from which coal samples were collected for study of the microfossil floras. The letters in parentheses after each number indicate which of the coals listed on the chart in Fig. 2 have been collected at each locality. Abbreviations of names of coal seams are as follows:

Waynesburg	*WB*	Winifrede	*WF*
Uniontown	*UN*	Chilton	*CH*
Sewickley	*S*	Hernshaw	*H*
Redstone	*R*	Cedar Grove	*CG*
Pittsburgh	*PG*	Campbell Creek	*CC*
Upper Freeport	*UF*	Powellton	*PW*
Upper or Middle Kittanning	*MUK*	Eagle	*E*
No. 5 Block (L. Kittanning)	*LK*	Cedar	*C*
Coalburg	*CB*	L. War Eagle	*LWG*
Buffalo Creek	*BC*	Gilbert	*G*

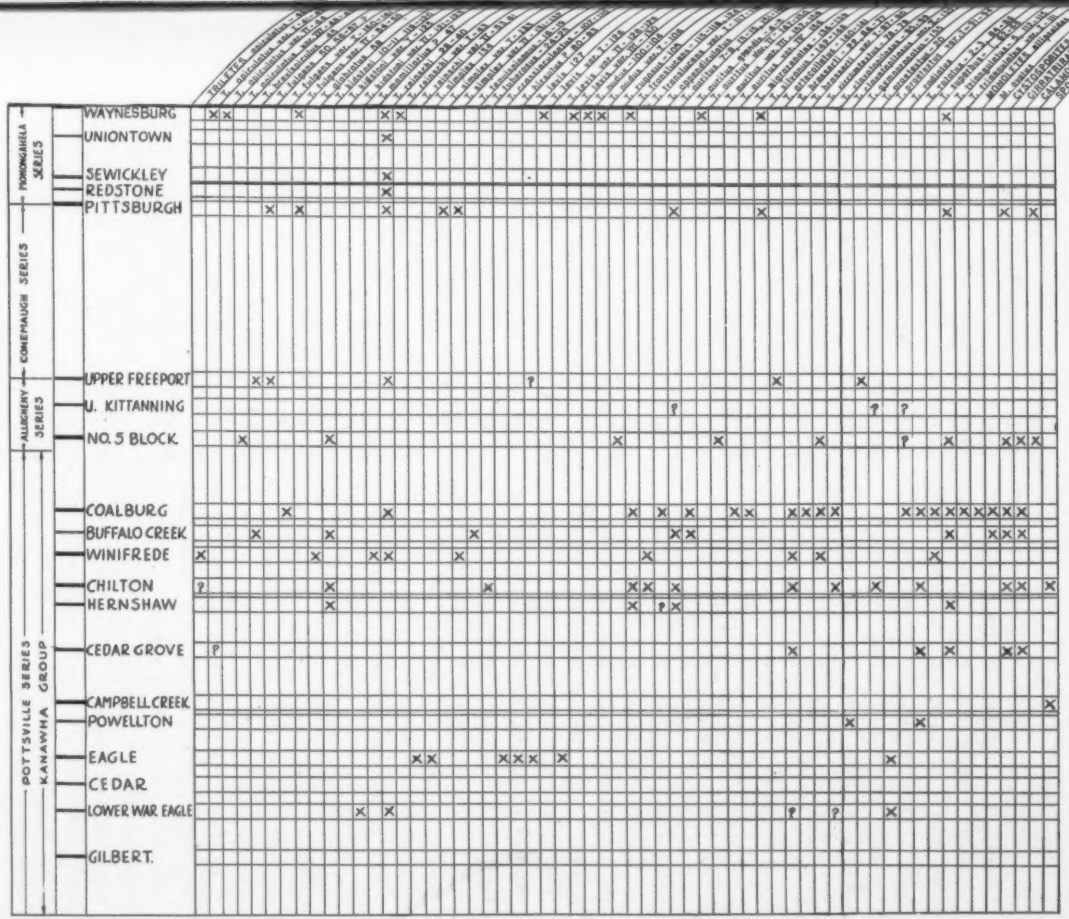


FIG. 2.—Chart placing twenty of the coal seams shown on map (Fig. 1) in relative position in the geologic column. The occurrence and distribution of megaspores of each of 54 species or varieties of *Triletes* and 6 species of 5 other genera are indicated by an × or by a "?" where specific identity is uncertain. Many other unidentified spores have been found which are not recorded here.

examined. In the excellent section given by David B. Reger[2] for the Pennsylvanian of West Virginia, 91 cycles of deposition are shown. These include a total of 102 named coal horizons. Most of these cyclothems contain a principal coal seam, and many, especially in the Kanawha group, include an additional coal, which may be locally important. Altogether, about 60 seams in West Virginia have been mined or might be considered to be of economic value. It will be noted in Figure 2 that the occurrence of microfossils is given for only 20 of these. Samples have been examined from all economic coal seams of the Pennsylvanian system shown by Reger, except the Little Clarksburg and the Elk Lick coals of the Conemaugh and the coals of the Pocahontas group. For reasons which are not clear, the microfossils separable from the residues of the coals below those of Kanawha age are not distinct or numerous in the samples examined. It is likely that the increase in rank of coal has been accompanied by volatilization of most of the waxy materials, and it is also possible that the early Pennsylvanian floras and/or their environmental conditions may have been sufficiently different from those which followed to explain in part the observed paucity of microfossils.

In several places it has been possible to obtain samples from a series of consecutively younger coal horizons, which are exposed almost continuously along recent road cuts and railroads. In Logan and Mingo counties in southwestern West Virginia, a relatively continuous outcrop of mid-Pennsylvanian strata is exposed for nearly 40 miles (Localities Nos. 24–27, Fig. 1). From Kanawha beds at the eastern base of Blair Mountain, a sequence can be traced up to the Upper Allegheny strata and back down to mid-Kanawha in the traverse of U.S. Highway 119 (and the fire-tower road) over the mountain to the Guyandot River at Stollings. From there, owing to the regional dip, consecutively older strata nearly to the base of the Kanawha group are exposed in almost continuous sequence upriver to Gilbert. From Gilbert the section continues back up through all the Kanawha into the Lower Allegheny strata at the top of Horsepen Mountain. In the complete traverse all coal horizons from the Gilbert to the No. 5 Block (Lower Kittanning) are exposed at two or more places, and, in addition, coals up to the Lower Freeport are exposed along the fire-tower road on Blair Mountain. All 37 coals or coaly horizons exposed have been sampled at each locality, and some of the results are recorded here.

Nearly comparable series of exposures in Breathitt and Pike counties, Kentucky (Localities Nos. 36 and 40, Fig. 1), have been studied, and the results of preliminary examination of coal residues are included here.

A relatively continuous section of Monongahela strata from Belmont County, Ohio (Locality No. 30, Fig. 1), recently published by George W. White,[3] and some even more complete sections taken from drill cores (Locality No. 29, previously mentioned) in Washington County, Pennsylvania, show all named coal zones and some additional coaly horizons of the Monongahela and all the Washington formation coals of the Permian strata above. The examination of the macerated residues from these coals

[2] "Pennsylvanian Cycles in West Virginia," *Ill. Geol. Surv. Bull. 60* (1931), pp. 220–31, Figs. 51–52.

[3] "Upper Pennsylvanian and Lower Permian Rock Section at Blaine Hill, Belmont County, Ohio," *Ohio Jour. Sci.*, Vol. XLV (1945), pp. 173–79.

is in progress, and some results are available for this report.

NATURE OF SAMPLES

The samples collected from the various coal horizons differ in nature. Most good exposures of coal seams were sampled by benches, or, where definitive boundaries are absent, samples were taken at regular intervals through the seam. For instance, the Pittsburgh coal seam, in regions of good development of its partings and overlying "A," or Rider and Rooster coals, has been divided to yield as many as 17 samples at one exposure, whereas in the poorly developed marginal areas of the field, such as at Locality No. 34 (Fig. 1) in Monroe County, Ohio, only a channel sample was deemed to be useful. Occasionally, a channel sample of a thick seam was taken, especially where exposure was poor and either the top or the bottom of the bed was concealed. In many instances it was possible to obtain only a sample of the "blossom" of a coal seam, i.e., a mixture of weathered coal fragments and soil mantle. These fragments appear to be satisfactorily representative of the coal from which they are derived and are much easier to prepare for study than are unweathered coal samples.

Many of the samples obtained from the long series of exposed strata discussed above represent thin streaks of attrital coal or coaly shales. Coaly streaks, which are determined to be merely single vitrain bands, a common occurrence in roof shales and sandstones, were not sampled, for it is assumed, and in many cases it is demonstrable, that they usually represent individual coalified fragments of allochthonous (drift) vegetal matter, such as stems and leaves. The thin attrital coals and coaly shales were sampled, for they are often representative of a coal horizon which is better developed elsewhere. Such horizons may often be identified in the field by their positions relative to other recognizable key beds. Occasionally, such layers may be discovered by special examination in thick series of shales which are without distinctive breaks, thus bridging facies changes and apparent depositional unconformities, where several beds, including a coal seam, appear to be missing.

PREPARATION AND STUDY OF SAMPLES

A portion of each sample was subjected to a maceration treatment for freeing the microfossils from the other coal constituents. Such techniques have been described by various workers, so it will suffice to say here that satisfactory results are obtained by using any of several variations of the Schulze[4] or Reinsch[5] methods, depending on the nature of the sample. Weathered coals break down more quickly and more satisfactorily than unweathered samples of the seams. Splint coals are more resistant to the oxidation process than are most other coal types. A complete review of the maceration techniques employed on all ranks and types of coal and a statistical summary of results is in preparation.

Each residue was separated into two sizes by being passed through a screen (Tyler Standard No. 65, opening *ca.* 208 μ). The coarser residues contained a variety of plant fragments—large spores, cuticles of leaves and stems, bits of wood (fusain), fragments of the vascular ele-

[4] Franz Schulze, "Über das Vorkommen wohlerhaltener Zellulose in Braunkohle und Steinkohle," *Ber. k. Akad. Wiss. Berlin* (1855), pp. 676–78.

[5] P. F. Reinsch, *Micro-palaeophytologia formationis carboniferae*, Vol. I: *Continens Trileteas et Stelideas* (Erlangen: Theo. Krische, 1884).

ments, etc.[6] These residues were examined under Greenough type binoculars, and recognizable plant remains were lifted out with special needles or brushes. The selected microfossils were then stored in vials of glycerine-alcohol; mounted dry on regular, black-cardboard microfossil slides; or, if translucent, mounted in thick balsam or glycerine jelly on glass slides and covered with cover slips. The fine residues were transferred to vials of glycerine-alcohol, and, from these, small portions were stained and mounted in Canada balsam or Diaphane on regular slides.

In identification of the microfossils it is necessary to examine a rather large number of specimens of the same type in order to understand possible variations and differences of appearance depending on the nature of preservation. Some specimens may be flattened normally in one direction, but occasionally they are compressed in a different plane and thus are of considerably different appearance. Specimens may be broken, partially or completely stripped of characteristic ornamentation, or distorted by the effect of adjacent sand grains or hard plant fragments. Often it is necessary to disregard some of the problematical forms as undeterminable. Some microfossils are consistently well preserved and complete, others as consistently poorly preserved. Such conditions are in line with those to be expected, according to observations made on recent deposits, such as bog and lake sediments.

IDENTIFICATION AND CLASSIFICATION OF MICROFOSSILS

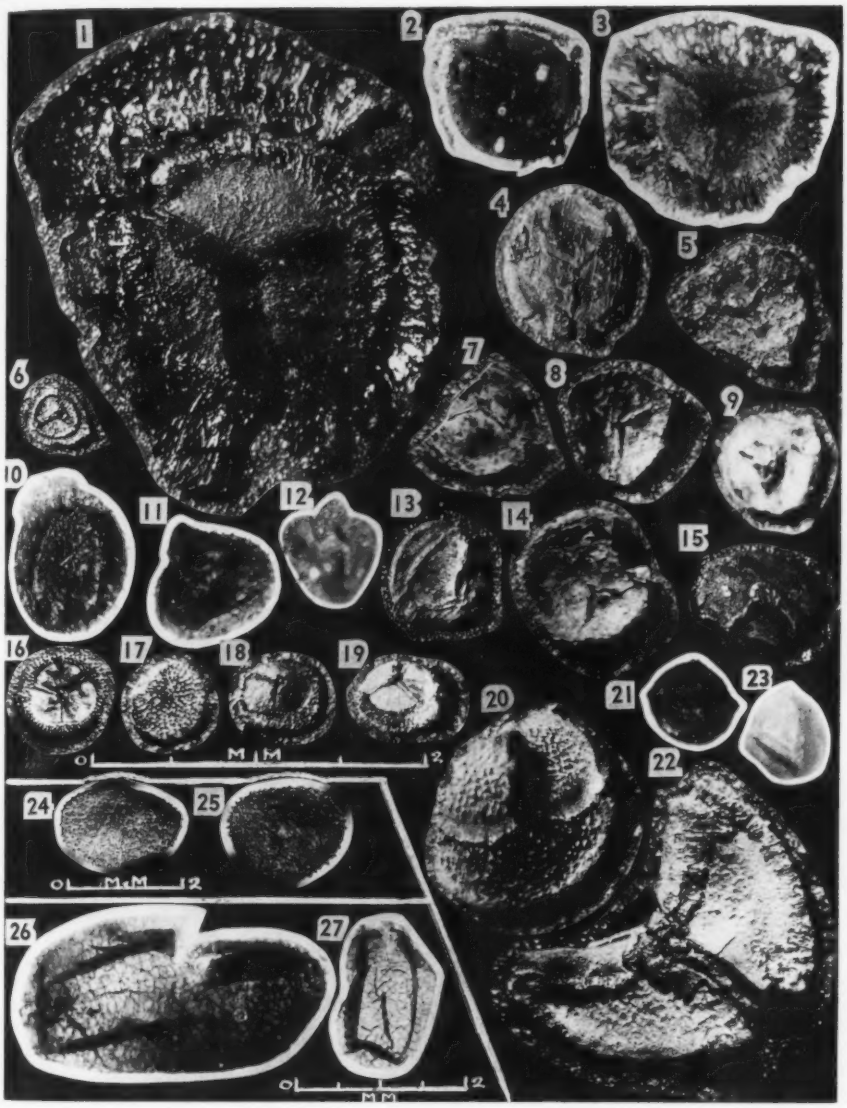
The principal identifiable plant parts preserved in coal are cutinized tissues, pollen grains, spores, and altered wood tissues. During maceration processes these are freed from the complex black humic substances, mixtures of partially decomposed plant remains, and mineral matter. The cuticular remains, i.e., cutinized epidermal tissues and continuous waxy layers (cuticles), are presumed to be of value for determination of the types of plants represented and may be shown to be of index value for coal seams. Isolation of large numbers of these from various coal seams has been carried on, but no identification has yet been attempted in the present study.

Pollen grains and spores are not homologous structures. Therefore, it is desirable to be specific as to which is under consideration. A strict botanical definition here would probably be confusing; hence it may be said, with reservations, that pollen grains are microscopic plants composed of several cells enclosed in a special covering, which develop from spores that have not been shed from the male portion of a flower (stamen, microsporophyll). The pollen grain itself is shed and transferred to the female flower structure (pistil, megasporophyll) by gravity, wind, or insects. Spores, as they are shed from ferns, mosses, and other plants of lower evolutionary rank than the seed plants, are unicellular, microscopic bodies enclosed by a special covering of somewhat similar nature to that found on pollen grains. Spores of these lower plants are shed and carried about by air currents (or distributed by gravity in the case of a few very large types). If they eventually come to rest on a suitable medium, they may germinate and grow into the sex-bearing (gametophyte) plant of the life-cycle. James M. Schopf[7] gives a good discussion of the

[6] Louis C. McCabe, "Some Plant Structures of Coal," *Trans. Ill. Acad. Sci.*, Vol. XXIV (1931), pp. 321–26, Pls. I–II.

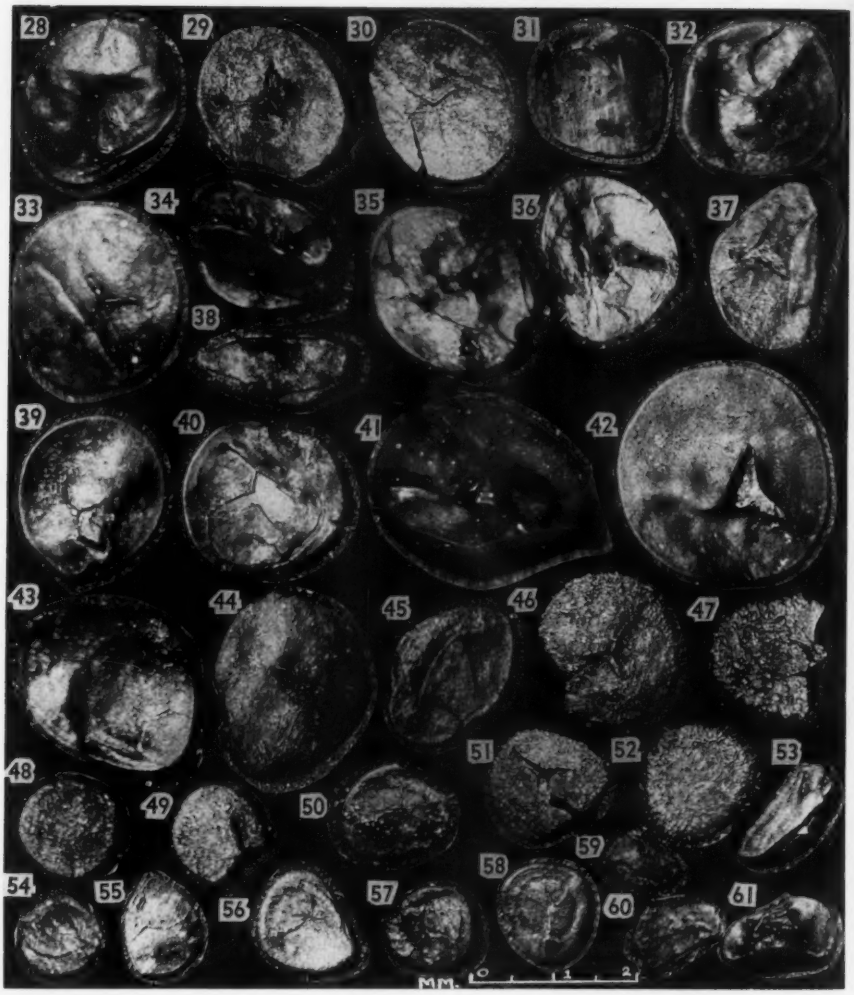
[7] "Spores from the Herrin (No. 6) Coal Bed in Illinois," *Ill. Geol. Surv., Rept. Investigations No. 50* (1938), pp. 10–15.

PLATE I



FIGS. 1–27.—Figs. 1–25, assortment of megaspores of the genus *Triletes* assembled to illustrate range of size, form, and ornamentation. 1, *T. superbus;* 2–3, *T. rotatus;* 4–5, *T. auritus grandis;* 6, *T. triangulatus;* 7–9, *T. auritus;* 10–11, *T. kidstoni;* 12, *T. levis*(?); 13–15, *T. auritus;* 16–19, *T. tenuispinosus;* 20, *T. praetextus;* 21, unidentified species; 22, *T. brasserti;* 23, undetermined species; 24–25, *T. tuberosus.* Figs. 26–27, unidentified sporangia.

PLATE II

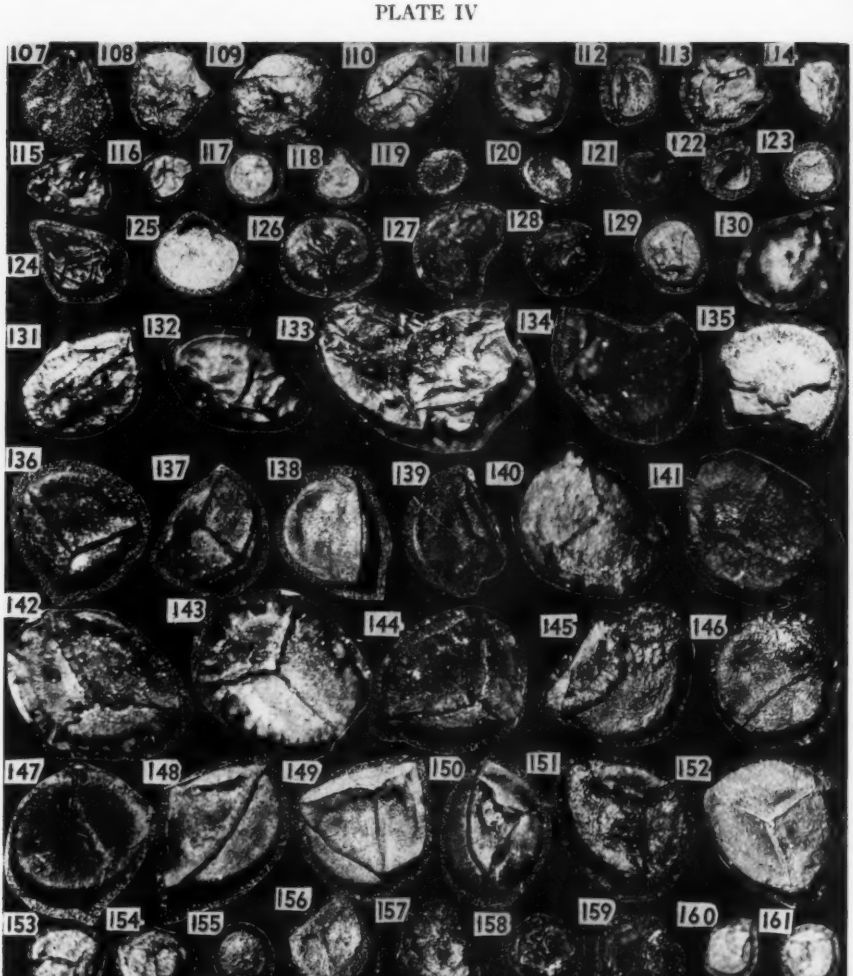


FIGS. 28–61.—Figs. 28–58, 61, genus *Trilletes*, section *Aphanozonati;* Figs. 59–60 spores of uncertain affinity. 28–40, *T. reinschi;* 41–42, *T. apiculatus* var. I; 43, *T. reinschi* var. I; 44, *T. apiculatus* var. II; 45, *T. brevispiculus;* 46, *T. apiculatus;* 47, *T. mamillarius*(?); 48–49, *T. apiculatus* var. III; 50, *T. fulgens;* 51–52, *T. apiculatus;* 53, *T. reinschi* var. II; 54–55, *T. fulgens* var. II; 56–57, *T. fulgens*(?); 58, *T. glabratus;* 59–60, *Sporites plicatus;* 61, *Trilletes reinschi* var. II.

PLATE III

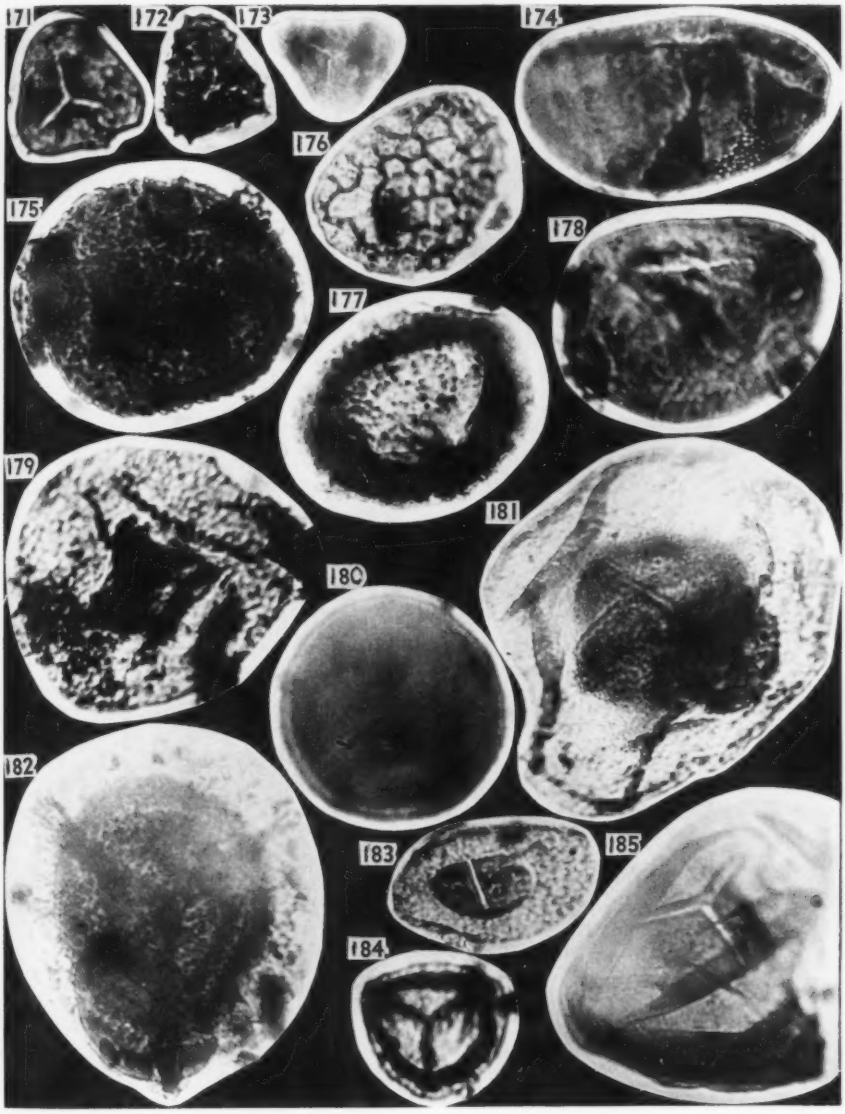
FIGS. 62–106.—Figs. 62–79, 84–99, genus *Triletes*, section *Triangulati* and undifferentiated spores; Figs. 80–83, 100–106, section *Lagenicula*. 62–65, *T. superbus;* 66–77, *T. brasserti;* 78–79, *T. circumlextus;* 80–83, *T. hirsutus*(?); 84–86, *T. rotatus;* 87–90, *T. brasserti* var. I; 91–94, *T. praetextus* var. I; 95–99, *T. clavatopilosus;* 100–104, *T. nudus;* 105, *T. rugosus;* 106, *T. nudus* var. I.

PLATE IV



FIGS. 107–70.—Figs. 107–10, 115–18, 124, 126–30, genus *Triletes*, section *Lagenicula;* Figs. 136–39, 142–52, 156–59, section *Auriculati;* Figs. 111–14, 135, 140–41, 155, section *Triangulati;* Figs. 119–23, 125, 131–34, 160–61, section *Aphanozonati;* Figs. 153–54, 162–70, undetermined species. 107–10, *T. crassiaculeatus;* 111, *T. triangulatus* var. I; 112–14, *T. triangulatus;* 115–116, *T. translucens;* 117–18, *T. translucens* var. I; 119–20, *T. kidstoni;* 121–23, *T. kidstoni* var. I; 124, *T. translucens;* 125, *T. kidstoni* var. I (occurs in Lower War Eagle Coal); 126, *T. levis* var. I; 127, *T. levis;* 128–29, *T. levis* var. II; 130, *T. levis* var. III; 131–32, *T. simplex* var. II; 133, *T. simplex* var. I; 134, *T. simplex;* 135. *T. clavaltopilosus* var. I; 136–39, *T. nigrozonales;* 140–41, *T. artecollatus;* 142–46, *T. silvanus;* 147–50, *T. auritus* var. II; 151–52, *T. auritus;* 153–54, undetermined species; 155, *T. gymnozonatus;* 156, T. *auritus* var. IV; 157–59, *T. auritus* var. III; 160–61, *T. fulgens* var. I; 162–70, undetermined species.

PLATE V



FIGS. 171–85.—Representative microspores from the Powellton, Campbell Creek and Alma coals selected to illustrate a number of genera from the Appalachian Basin. 171, *Punctati-sporites* sp., 33 × 36 μ; 172, *Granulati-sporites granulatus*, 20 × 24 μ; 173, *Granulati-sporites* sp., 17 × 20 μ; 174, *Laevigato-sporites* sp., 43 × 75 μ; 175, *Granulati-sporites* sp., 80 × 90 μ; 176, *Reticulati-sporites* sp., 43 × 50 μ; 177, *Denso-sporites* sp., 39 × 50 μ; 178, *Laevigato-sporites* sp., 46 × 60 μ; 179, *Denso-sporites* sp., 53 × 58 μ; 180, unidentified *Sporites*, 53 × 58 μ; 181, *Endosporites ornatus*(?), 115 × 125 μ; 182, *Cirratriradites* sp., 110 × 115 μ; 183, *Endosporites* sp., 30 × 50 μ; 184, *Lycospora confinis*, 37 × 42 μ; 185, *Calamospora* sp., 105 × 115 μ.

morphology and terminology of spores and their equivalents. It is often not possible to distinguish whether one has spores or pollen grains under observation, for usually nothing more than the multiple coat or covering is preserved. The presence of cell contents or structures is required for certain determination.

The spores of a plant may be all alike in appearance, a condition called "homospory" or "isospory," or they may be divisible into two groups originally distinguished on the basis of size, a "heterosporous" condition. The larger spores are called "megaspores" and are more often the female spores. "Microspores," the smaller type in the heterosporous condition, are usually male. A consideration of the fact that microspores have been shown to be larger than their corresponding megaspores in some instances—an important point in botanical studies—would seriously confuse the points being drawn here and so will not be discussed. The generalizations made are adequate to introduce required terminology. The sexes cannot be conclusively proved for fossils, and, further, the microspores are indistinguishable from "isospores" in many cases. The study of the microspores has not progressed far enough to give any major conclusions based on them in this paper. Figures 171–85, Plate V, are typical representatives of 10 genera of microspores. Plates I–IV are made up of examples of sixty species or varieties of spores, mostly megaspores, distributed through six genera.

DESCRIPTIVE TERMINOLOGY OF SPORES

Two basic requirements for any student or technician working with microfossil floras are the mastery of the understanding of the morphology of spores and pollen grains and the accumulation of an adequate, direct, simple vocabulary to discuss or describe each fossil. Even a basic terminology may at first appear to be too complicated, too detailed, or too picayune to be of practical value. However, a straightforward presentation of the terms, accompanied by simple diagrams, such as those given by J. M. Schopf,[8] should be readily understandable. Recently G. Erdtman, in chapter v of his comprehensive book, *An Introduction to Pollen Analysis*,[9] brought together a well-illustrated and clearly written description and glossary of pollen and spore morphology and terminology. A portion of the material given there is properly credited to the two other outstanding treatments of this subject by R. Potonie[10] and by R. P. Wodehouse.[11]

Spores usually occur in either of two principal forms. One form, represented by the spores shown in Figures 174 and 178 (Pl. V), is of a somewhat "beanlike," slightly elongate shape, i.e., bilaterally symmetrical. A slitlike opening, the monolete aperture, is evident on the upper surface. In contrast to these, radially symmetrical spores are distinctive (Pl. I, Fig. 1). They are usually marked on one surface with a triradiate scar or figure. This is called a "triradiate tetrad scar" because of its origin during the formation and the development of these spores in tetrahedral groups. Figures 72–75 show examples of tetrads of spores in their original tetrahedral groupings. When these groups are broken or

[8] "The Paleobotanical Significance of Plant Structure in Coal," *Trans. Ill. Acad. Sci.*, Vol. XXVII (1936), p. 109, Figs. *A–C*.

[9] Waltham, Mass.: Chronica Botanica Co., 1943.

[10] "Zur Mikrobotanik der Kohlen und ihrer Verwandten. I. Zur Morphologie der fossilen Pollen und Sporen," *Arb. Inst. f. Paläobot. u. Petrogr. d. Brennsteine*, Vol. IV (1934).

[11] *Pollen Grains* (New York: McGraw-Hill Book Co., 1935).

forced apart, the component spores appear individually as those single spores shown in Figures 66–70. Bilateral spores usually develop in linear or cruciform series of four, and such tetrads are rarely found intact.

Spores, either radial or bilateral, are generally oriented in a particular way for comparative study and description. The proximal (inner in relation to original grouping) and distal (outer) sides, or halves, of radially symmetrical spores are illustrated by Figures 66 and 69, respectively. The rays of the triradiate tetrad scar, which develop at the edges of the contact areas (portions of surface of a spore which were in contact with adjacent spores of the tetrad), may extend from the apex (center) to the equator (margin) of the proximal side (Figs. 87, 143) or partway to the equator (Figs. 14, 18, 185); or these rays may extend beyond the margin of the spore body onto a peripheral flange, a structure which is formed by an unusually great development of the arcuate ridge which sometimes borders the outer edge of each contact face (Fig. 182). The interradial contact areas (contact faces between rays of triradiate scar) may be called "pyramic areas." They often differ in surface texture from any remaining peripheral zone of the proximal half of the spore body proper. Figures 16, 18, and 19 show clearly the smooth pyramic areas of the proximal side with a well-developed triradiate scar, which is more prominent at the apex than toward the equator. Bordering the smooth pyramic area in these figures, the arcuate ridges are scarcely visible, but they are well shown at the right and left center of the spore in Figure 20 and on the spores illustrated by Figures 40, 58, 149, and 156. Peripheral to these ridges in Figures 16, 18, and 19 a knobby or verrucose ornamentation of the surface extends to the equator. This ornamentation continues over the distal surface also, as may be seen in Figure 17, which shows the opposite (distal) side of the same spores. In a few cases the arcuate ridges coincide with the equatorial rim and may be further developed into a flange, as has already been suggested. Such flanges may be smooth and thin or leathery (Fig. 143), striated in texture (Pl. I, Fig. 1), or delicately dissected (Pl. I, Figs. 2, 3). Sometimes the flange or arcuate ridges show particularly strong development at the ends of the rays of the triradiate scar or angles of the spore body. Figure 139 shows clearly this type of auriculate or "eared" spore. In the center of some radially symmetrical spores is a trilete aperture, an opening (Figs. 185, 14, 40) which corresponds in function to the aperture found on some bilateral spores as stated earlier. Such apertures, or the split developing along the trilete suture, are the points of emission of the plant developing from the spore (gametophyte). The apertures are often masked by extra development of the spore wall along the rays. In one group of spores (section Lagenicula) an exceptional development of such accessory lips is important in the formation of a prominent, somewhat pyramidal apex, called a vestibule (Figs. 10–12, 100–104). Such apical development results in bottle-shaped or lageniculate spores, in which the polar axis (proximodistal axis through apex) is longer than the equatorial axis.

Further orientation in terminology may be derived from a careful study of the skilfully executed drawings and diagrams illustrating the basic plan of each of the genera of spores recognized in the Schopf-Wilson-Bentall treatise.[12]

[12] J. M. Schopf, L. R. Wilson, and Ray Bentall, "An Annotated Synopsis of Paleozoic Fossil Spores

PRINCIPLES OF INTERREGIONAL CORRELATION

The megaspore flora of the Appalachian coals has been found to include a number of species recorded from the Upper Paleozoic deposits of Europe, as well as from the interior fields of North America. It is hazardous to suggest precise relationships of plants or isolated plant entities, found in geographically distant places. Modern floras, however, show a strong genetic relationship between plants of different regions or continents, and in many cases even species are known to be distributed widely over the earth. Sometimes their distributions appear to be more strongly controlled by habitat or life-zone environments than by continental limitations and such continental barriers as mountains and deserts. It is on the premise that the controlling factors for plant distribution are much the same today as at other periods of the earth's history that we venture to assume that fossil plants of the Coal Measures of Europe may have been specifically related to those of the same period in North America.

Caution, however, must be observed in assigning specific epithets to fossil plants which are apparently indistinguishable but are of different geologic distribution. Many genera of plants today have been traced directly back through Late and Middle Tertiary, and some even further. Only a few of the many thousands of existing species, however, are believed to have a continuous record, even from the Miocene to the present. With an appreciation, then, of the long period of time included in the Permo-Carboniferous period or in the Pennsylvanian alone, it is necessary to use great discretion in assigning to a spore from the Monongahela formation, for example, the same name given originally to a specimen from the Kanawha or Westphalian A.

SPECIFIC CHARACTERISTICS AND POSSIBLE VARIATIONS IN A GENUS

Plate I (Figs. 1–25) was assembled to show, comparatively, some of the variation possible in spores assigned to a single genus. This genus, *Triletes*, is the largest and most complex known at the present time. Schopf, Wilson, and Bentall[13] recognize 95 species to be included within it, some of which are of Mesozoic age.

Many of these are admittedly of doubtful status, some probably are conspecific with species already established, others may be of subspecific rank. Schopf, at the meeting of the Paleontological Society of America in 1936, proposed a division of *Triletes* into four groups or sections. Previously, other section names had been suggested, all but one of which (Lagenicula, Bennie and Kidston) appeared untenable to Schopf because of the unnatural relationships resultant from such grouping. He later restated these sectional divisions, Aphanozonati, Lagenicula, Auriculati, and Triangulati, and appended a description to each.[14]

At the top of the chart in Figure 2 the list of 60 kinds of spores includes 54 presumed to belong to *Triletes*. They have been grouped there, as nearly as possible, into the sections described by Schopf. In each group the species and varieties have been given in alphabetical order, and each name is referred by number to its illustration(s) in Plates I–IV.

and the Definition of Generic Groups," *Ill. Geol. Surv., Rept. Investigations No. 91* (1944), Pls. I–III.

[13] *Ibid.*, pp. 18–27.

[14] Pp. 17–24, 27, 30, 31 of ftn. 7.

The range in size is suggested by a comparison of (Pl. I, Fig. 1) one of the largest megaspores with Figure 6. These species, *T. superbus* and *T. triangulatus*, respectively, both have prominent equatorial appendages. The spore body of the former, therefore, is not so large as *T. reinschi* (Figs. 28–40). The largest megaspores belong to the genus *Cystosporites*, which is not figured here. They range up to 2–3 cm. in length. All others are generally less than 3 mm. in diameter. The smallest that can be conveniently picked out of the residues by manual manipulation are of about 300μ in diameter.

Equatorial or zonal appendages are prominent features of such spores as those shown in Plate I, Figures 1–3 and 6, but are less prominent in auriculate forms, such as those shown in Figures 4, 9, and 13–15. Often the flange of a spore may be broken off before or during fossilization or in maceration. Therefore, the intimate characteristics of the spore body itself must be recognized for proper identification. Figure 22 shows the spore body of *T. brasserti*, with the flange missing. There may be considerable variation in width of flanges in the same species, as shown by a comparison of *T. rotatus* in Plate I, Figures 2 and 3, and in degree of dissection. It is extremely difficult, if not impossible, to draw the line between species which have been founded solely on variable characteristics of this sort.

Variations of a triradiate tetrad scar are illustrated by the series of Figures 8, 16, 19, 3, 1, and 22 (Pl. I), in that order of increasing prominence, and Figures 14, 5, 8, 16, and 3, in the order of increasing length of rays. Apical structures of increasing prominence are shown in the comparison of *T. tenuispinosus* in Figures 16, 18, and 19 with *T. levis* in Figure 12 and *T. kidstoni* in Figures 10 and 11. The strongest development of this type is shown by such a species as *T. nudus* in Figures 100–103.

All the foregoing features are presumed to be genetically derived in the development of the spore and may be termed "haptotypic" characters. Genetically determined characters should be reasonably constant and should afford bases for separation of organisms into major groups.

Such features as surface ornamentation, however, appear inconstant and can be used only for varietal or perhaps specific distinctions. Schopf[15] has illustrated a practical terminology for such emphytic characters. Figures 12 and 23 show a smooth or levigate surface. The pyramic areas of *T. tenuispinosus* in Figures 16 and 18 are finely punctate or granulose; in *T. brasserti* (Fig. 22) and *T. superbus* (Pl. I, Fig. 1) they appear verrucose and verrucose to spinose. Toward the edge of the pyramic area in Plate I, Figure 1, the surface is covered with hairlike protrusions which peripherally grade insensibly into the rami of the flange. Actually, the flange *appears* to be made up of a dense mat of these hairs, irregularly fused together. The pyramic area in *T. praetextus* (Fig. 20) is very rough or verrucose, much the same as the rest of the spore surface, but in Figures 16–19, the granulose texture of the pyramic area is markedly differentiated from the spinose spore body. In *T. kidstoni* (Fig. 11) the spines are hooked, more slender, and less numerous, whereas in *T. tuberosus* (Figs. 24 and 25) they are strong and tuberculate.

Sporelike bodies similar to those shown in Figures 26 and 27 have been found in widely separated horizons of the Pennsylvanian. They vary greatly in

[15] Explanation of Fig. *C*, ftn. 8.

size, but, by the nature of the reticulation on the inner surface of the transparent wall, they appear to be sporangia, i.e., the spore-bearing sacs, possibly of certain calamitean plants.

Differences in position and nature of preservation, in maceration, and in conditions of observation may result in apparent variations of spore bodies. Figures 4, 5, 7–9, and 13–15 may be compared in these respects. Figures 7, 9, and 14 show *T. auritus* compressed axially. Examples of this species in Figures 13 and 15 are compressed in an equatorial plane, thus showing parts of both proximal and distal halves. Figure 9 is brightly illuminated, and reflection from the dense black surface makes the spore appear light and nearly obscures the prominent infolded "ear" on the upper right-hand margin. Figure 13 is illuminated satisfactorily and shows the arcuate ridge (at left) between the ends of two rays of the trilete mark which converge at the apex (lower right). Figure 15 is very weakly illuminated but shows the dark color and granular texture of the surface. The arcuate ridges extend from upper left to lower right; and, since in this species the arcuate ridges nearly coincide with the equatorial rim, it may be said that the lower left portion of the picture is part of the proximal half and that the upper right (crescent-shaped) portion is distal. One ray of the trilete mark extends across the proximal area and is concealed at its peripheral (equatorial) extremity by a boss or knob which is actually an "ear" of this auriculate form. The "ears" may be preserved in an extended condition (lower right of Fig. 5) or folded over the body as already mentioned (upper right of Fig. 5). The pyramic area of Figure 7 shows some roughened areas, which are patches of weakly developed spines; but in Figures 4 and 5, on a variety of this species, *T. auritus grandis*, the roughenings are caused by extraneous matter adhering to the spore, an indication of undermaceration. The trilete aperture in Figure 14 is open, and the spore shown in Figure 8 would present the same type of opening if it were split along the rays of the trilete figure. Such variation in openings appears to be due to various happenings either before or during preservation, compression, or maceration.

Such instances of variation among different specimens of the same species could be multiplied indefinitely. This variability is the most difficult problem for the student of such fossils. It is the basic reason for the confusion which exists in their taxonomy, for the actual *specific value* of the variations has not been determined.

DISCUSSION OF THE GENUS *Triletes*, SECTION APHANOZONATI

All the figures on Plate II represent species of the section Aphanozonati, with the exception of two spores of uncertain relationships (Figs. 59–60), referred to *Sporites plicatus*. They are believed to be spores of certain large lycopods, because many similar spores have been isolated from spore-bearing structures (strobili) of *Lepidodendron* and *Sigillaria*.

This group is typified by *T. reinschi* (Figs. 28–40). Aphanozonate spores lack flanges and other equatorial appendages, but arcuate ridges are normally evident (Figs. 40, 56, 58). The spore coat is usually thick and has considerable variation in ornamentation, from smooth (Figs. 33, 32) to spiny (Figs. 46, 51) or knobby (Fig. 47). Included in this group are some of the largest megaspores, ranging in diameter up to about 3 mm. The triradiate mark (Fig. 33) or aperture (Figs. 29, 37, 40, 42, and 46) is usually restricted to

less than one-half the diameter of the proximal surface.

T. reinschi (IBRAHIM) SCHOPF (FIGS. 28–40)

This species is fairly common throughout the Pennsylvanian coals of the United States. It is regarded by Schopf as having a long range in the coals of Illinois; and in the Appalachian region it is found from the Gilbert coal (near the base of the Kanawha group) to the Waynesburg. It is locally abundant in several seams.

It is a large spore, varying from 1,700 to 2,700 μ, usually circular in outline and flattened axially. The surface is rather smooth and varies from dull black to light brown. The pyramic area is defined by a low arcuate ridge, which is often difficult to discern. The rays of the aperture are slender, extending one-third to one-half the radius of the spore, and they end in an acuminate tip. They are often split open along these sutures (Figs. 29, 37). The interradial areas of the spore are occasionally plicate. These folds are irregular but extend radially from the apex.

In some instances the distal surface has a few short tubercles irregularly distributed. These are rarely found on the proximal surface and never in the pyramic area. Other forms appear minutely pustulose. These types may actually be varietally or specifically different.

Two varieties of special nature are shown. Figure 43 is of a form found in the Waynesburg coal. It seems to have a more conspicuous pyramic area, which appears convex in flattened state. The first of these found was presumed to have had the outline of another spore impressed on it, coinciding with the pyramic area, but subsequently discovered specimens make such a speculation improbable.

Figures 53 and 61 are of spores from the Eagle coal. They are usually folded, somewhat triangular in outline and smaller than, but otherwise similar to, *T. reinschi*. There are no hairs or peculiar markings, but the surface is finely granulose. It does not appear to be assignable to *T. fulgens* or *T. glabratus* but may be a small *T. reinschi*.

T. apiculatus (IBRAHIM) SCHOPF, WILSON, AND BENTALL (FIGS. 46, 51–52)

A relatively large, gibbous spore, the *T. apiculatus* is irregular but not angular in outline and is 1,500 μ in average diameter. The body is covered both distally and proximally, except in the restricted pyramic area, by large papillae or apiculae. These are higher than broad, distally bent or recurved, and terminated by sharp points. The pyramic area is demarcated principally by lack of these large apiculae, though numerous short spines or pustules are present. The arcuate ridge at the periphery of this area is very inconspicuous, but it does completely outline the area. The rays of the trilete aperture are small and narrow, usually extending not more than one-third the distance to the periphery of the proximal side. They form no prominence at their juncture in the center. The exine appears to be thick and opaque.

It has similarities to *T. brevispiculus* Schopf and to *T. mamillarius* Bartlett and to some specimens of the Type 14 of Zerndt. This species is recorded from Namurian and younger rocks of Europe and has not been found above the Kanawha group here.

Three varieties are also illustrated. One variety, *T. apiculatus* var. I (Figs. 41 and 42), is a giant form, 3 mm. in diameter. It is sparsely spinose, and very long, fine hairs are conspicuous along the rays. Portions of the surface are pustu-

lose. It appears to be intermediate between the unornamented *T. reinschi* type and *T. apiculatus sensu stricto*. The second, *T. apiculatus* var. II (Fig. 44), is another form intermediate between *T. reinschi* and *T. apiculatus*. In this variety the pyramic area is greatly reduced, and the trilete scar is distinct but delicate. The interradial areas are finely folded (plicate). Variety III (Figs. 48–49) is only 1,100 μ in average diameter, with long trilete rays, which are developed prominently at the apex. The coat is rough but not knobby, and true hairs are lacking.

T. brevispiculus SCHOPF (FIG. 45)

This is a moderately thin-walled, light-brown megaspore, with scattered mammillate papillae. This species, so far found only in the Upper Freeport coal, coincides remarkably with the description given by Schopf.[16] The pyramic area does not show in this photograph, for the nature and distribution of spines over the tan surface were deemed most important for illustration. An unusual instance of correlation is afforded by this species, for Schopf's material is from the No. 6 (Herrin) coal of Illinois, near the top of the Carbondale series. The position of this coal, as may be seen on the National Research Council's correlation chart,[17] is presumed to be close to that of the Upper Freeport, which is near the top of the Allegheny formation. Additional studies may extend the range of this species in either or both coal fields.

T. mamillarius BARTLETT (FIG. 47)

The spore is roughly globose, prominently marked by very strong, mammilliform papillae. The specimen shown here, which is from the Winifrede coal (Upper Kanawha), is broken. The spine bases show most clearly near the edge of the pyramic area, which is not well defined. A number of other species from Europe are closely related. The stratigraphic position of this and some other spores from Upper Pottsville coals of West Virginia may assist not only in placing the drift pebbles of coal, described by Bartlett simultaneously with the description of this and two other megaspores,[18] but also in establishing correlation of the Michigan coal seams with the Appalachian coals.

T. fulgens (?) ZERNDT (FIGS. 50, 56–57)

The identification of the spore types shown in Figures 50, 56, and 57 is not final. They have nearly twice the average diameter given for the species. Otherwise, Zerndt's figures[19] are certainly similar in general appearance. In the best specimen (Fig. 56) from the Pittsburgh coal horizon, the surface is dull and slightly roughened proximally and satin-smooth and black, distally. The form is somewhat gibbous, and strong arcuate ridges surround the pyramic area. There are prominent interradial plications.

The considerably younger age (Monongahela) of this material than Zerndt's, which is Middle Dinantian to Middle Namurian, in addition to difference in size, may be sufficient for specific differentiation.

[16] Pp. 26–27 and Pl. I, Figs. 13*a–r;* Pl. II, Fig. 6; Pl. III, Figs. 1–4, of ftn. 7.

[17] Pennsylvanian Subcommittee, "Chart No. 6. Correlation of the Pennsylvanian Formations of North America," *Bull. Geol. Soc. Amer.*, Vol. LV (1944).

[18] Harley Harris Bartlett, "Fossils of the Carboniferous Coal Pebbles of the Glacial Drift at Ann Arbor," *Papers Mich. Acad. Sci. Arts, Letters, 1928*, Vol. IX (1929), pp. 11–25, Pls. XIII–XV.

[19] Jan Zerndt, "Les Megaspores du bassin houiller polonais. II," *Acad. Polon. Sci. Lett. Trav. Geol. No. 3* (1937), p. 5, Pl. I, Fig. 2; Figs. 1–9; and "Megasporen als Leitfossilien des produktiven Karbons," *Acad. Polon. Sci. Lett. Bull. Internat.*, Ser. B (1931), p. 171, Pl. III, Figs. 9–10.

One variation shown here, *T. fulgens* var. II (Figs. 54 and 55), is a little smaller and lighter in color, with a thinner spore coat and much less conspicuous arcuate ridges. In some respects this more nearly resembles Zerndt's material than those described above. Figure 55 shows a specimen flattened equatorially, with the spore broken open (at top of picture) along the trilete process.

A second variation, to be found in Plate IV, Figures 160–61, is about 600 μ in diameter with features very similar to variety II, above, except that the pyramic area occupies nearly all the proximal surface.

T. glabratus ZERNDT (FIG. 58)

This is a rather distinctive spore, which is of the same general plan as *T. fulgens*, but it has a number of characteristic features of specific value. This figure is closely comparable to Figures 2 and 3 of spore Type 9 in Zerndt's "Megasporen aus einem Flöz in Libiaz (Stéphanien)."[20]

Triletes glabratus is a very black, gibbous spore, with some roughening apparent on the dull surface. In the equatorial region it is slightly and finely pustulose, with slender, short hairs. The arcuate ridges are accentuated by the thinness of the wall in the pyramic area, which thus appears sunken. The trilete rays converge at the apex to form a small boss, and they expand radially, gradually blending on either side with the arcuate ridges. They often falsely appear to be extended beyond these ridges because of the presence of a broad fold or sinus, terminal to each ray. This species, from the Upper Kanawha, occurs approximately at the level of the base of the long European range given by Zerndt.

[20] *Ibid.* (1930), Pl. I.

T. simplex (ZERNDT) SCHOPF, WILSON, AND BENTALL (FIG. 134)

The large (1,700 μ) coarse spore has a rough, dark-brown coat, which is somewhat convoluted. The tumorous structure toward the left in the figure is the robust apex. The arcuate ridges are relatively weak. It is a peculiar fossil, with information lacking for systematic assignment. It has been found only in the generally poor residues from the oldest coals of the Kanawha.

Triletes simplex var. I is a larger spore with a thinner wall. Plate IV, Figure 133, shows two of a group of eight or ten which were pressed together in a mass isolated from the coal residue. The surface, in marked contrast to the rough, lusterless coat of *T. simplex*, has a vitreous luster and a minutely pitted surface. The walls here are moderately thin and much folded, and the trilete apparatus is usually obscured by the folds.

Triletes simplex var. II is a problematical variety (Figs. 131–32) and is shown here to be somewhat folded and with a thicker wall than variety I. The coat is tan and moderately translucent. These two specimens were recovered from the Pittsburgh and Winifrede coals, respectively.

T. kidstoni (LOOSE) SCHOPF, WILSON, AND BENTALL (FIGS. 10–11, 119–20)

The strong apical development apparent in Figures 10 and 11 is not typical for the species. The two specimens in Figures 119 and 120 show at upper left and upper right, respectively, a light, clear zone, which is the pyramic area. The spores are densely to moderately covered with thin, hooked spines. These two spores are more representative of the species, and they also show its comparatively smaller size than most of the

Aphanozonati. This species is very abundant in Upper Pottsville coals and often outnumbers all others in some benches. There are apparently several varieties, one of which may be represented by Figures 10 and 11.

Two forms, here considered to be at least of varietal status (*T. kidstoni* var. I and var. II), are from the Lower War Eagle coal. No intermediate occurrence of this type of spore between this horizon and Upper Pottsville is known. Variety II has strong arcuate ridges, with a slight thickening at the angles of the spore. Mammilliform papillae are loosely scattered over the surface, except for the extremely smooth pyramic area. As in *T. kidstoni*, this area is restricted to about one-third to one-half the proximal surface. Variety I is larger and has a stronger development of the apical processes. In fact, it is quite possible that a spore with the features shown in Figure 125 belongs to Lagenicula. These spores are among the best coal-index fossils of all the megaspores studied so far, because of their local abundance and apparent restrictions of geologic range. Additional work is required to determine their specific limitations.

T. tuberosus (IBRAHIM) SCHOPF, WILSON, AND BENTALL (FIGS. 24–25)

The species *T. tuberosus* was partially described earlier. It is another of the very strongly apiculate forms. The demarcation between this and several others is indefinite. It is exceedingly abundant immediately below the Winifrede limestone horizon (Upper Kanawha) in all the beds of the multiple Chilton coal seams.

T. tenuispinosus ZERNDT (FIGS. 16–19)

The features and characteristics of *T. tenuispinosus* have been discussed and illustrated in connection with the study of Plate I.

Sporites plicatus SCHOPF (FIGS. 59–60)

Although this problematical form is discussed at this point, it is not to be inferred that it is considered to belong to the Aphanozonati. It could be placed at the end of the entire résumé of spores but is treated here because of its inclusion in Plate II.

There are a number of spores which show such generalized features that they cannot be assigned to any group. A spore assigned to the genus *Sporites*, therefore, has little biological significance and will probably never be an aid to correlation. If the spores included in this "form genus" eventually become better understood, new groups will probably be made to receive them. Species assigned to this genus are not presumed to be related in any way. Apical structures of these spores, as shown in the figures, are usually obscured. They may have either a trilete or a monolete suture or neither. The wall of this "species" is folded and slightly translucent. Representatives of this heterogeneous group occur throughout the Pennsylvanian coals.

DISCUSSION OF THE GENUS *Triletes*, SECTION TRIANGULATI

The basic characterization of this group is less distinctive than desirable, and the determination of the spores to be included is difficult. Plate III was assembled to show some of the more conspicuous types. Figures 62–79 and 84–106 include spores of this group with the most conspicuous zonal appendages. In Plate IV several additional species are illustrated in Figures 111–14, 135, 140–41, and 155.

The name "Triangulati" is derived

from the somewhat triangular appearance of certain of these spores, an outline due to the unequal extension of the flange about an oval or circular spore body in some species. A number of spores included in this group are not so characterized. The pyramic area is usually large, and the arcuate ridges and other appendages are equatorial (or nearly so) in position. The trilete rays are usually quite long.

Schopf[21] suggests that spores assigned to the Triangulati represent such herbaceous lycopods as Lycopodites and Selaginellites. He believes that these groups and allied types are probably more important in coal formation than is usually recognized from macroscopic remains. They certainly have a prominent position in coals of the Upper Pottsville in the Appalachian field, although they are much less important, i.e., have fewer representatives, at earlier and later periods, according to an analysis of the spores studied to date. Two or three species(?) have extremely long ranges, however.

T. superbus BARTLETT (PL. I, FIG. 1; PL. III, FIGS. 62–65)

Several spores are so closely allied to this species that specific determination is difficult. Surely one or more other species may be conspecific with it. A detailed discussion of this species will suffice at this time for most of these closely allied spores.

Bartlett concluded his original description[22] of *T. superbus* with the statement that it was so named ". . . . because it is unsurpassed in size and beauty of form among all the spores that have been described from coal." His early paper well illustrates the striking features which characterize *T. superbus*, though the size is not so great as that of some other Paleozoic spores, as previously noted. Figure 1 (Pl. I) has been described in part. The body of the subtriangular spore is about 2,200 μ in diameter. The rays of the strong triradiate structure are cleft longitudinally and extend to the periphery. Each ray appears as a double band of "leathery fringe" standing on edge on the spore surface. The flange is composed of a convoluted series of fused cylindriform processes (rami), more thickly matted near the inner margin than peripherally. The entire spore body is usually covered with these hairlike processes, though toward the apex they are reduced in size and scattered less densely.

T. brasserti STACH AND ZERNDT (FIGS. 22, 66–77)

Triletes brasserti is a spore similar to *T. superbus*, with slightly coarser features. Figure 22 on Plate I shows clearly the exceedingly prominent bi-ridged rays of the trilete process, which is more strongly developed but otherwise similar to the preceding species. The distal side is essentially smooth (Fig. 69), but, toward the periphery, minute protuberances occur, which become larger peripherally to blend with rami of the flange. The flange is usually less than one-half the radius in width. For orientation, it may be noted that on the tetrads shown in Figures 72–75 only the distal side of each component spore is visible and that the flanges are developed at the margins of contact with the concealed faces of each adjacent spore. Figures 68, 76, and 77 show spores which were compressed equatorially instead of in the normal axial plane.

The spores portrayed in Figures 87–90 are probably a distinct variety. They are

[21] P. 32 of ftn. 7.

[22] Pp. 20–21 of ftn. 18.

usually smaller, with a very narrow flange. Another distinction is the slightly reduced pyramic area, a condition well shown in Figure 90. The flange is not quite coincidental in position with the equator.

T. circumtextus ZERNDT (FIGS. 78–79)

Triletes circumtextus is closely related to *T. brasserti* but is a smaller spore with more delicate features. It is closely comparable to the Type 18 of Zerndt, especially 18*a*, 18*c*, and 18*d* of his 1934 paper on "Les Megaspores du bassin houiller polonais."[23] The flange varies from one-third to one-sixth the diameter of the spore and from solid to reticulate or lacerate. It appears to be composed of anastomosed radial plates or fibers.

The surface is dull and minutely papillose in the pyramic area, and on the distal surface the papillae are larger, more numerous toward the periphery, and absent toward the center. This species has a slightly later range than *T. brasserti*, i.e., it is prominently developed in the Lower Allegheny, and appears to be the only one of these closely related species to extend so high in the section, according to present records of observation.

T. rotatus BARTLETT (PL. I, FIGS. 2–3, 84–86)

The most conspicuous feature of this spore is the unusually delicate structure of the flange. It is composed of a number of slender, sinuous processes which radiate from the spore body at wide intervals and fuse together by lateral branches at the extreme periphery to form a narrow rim. Figure 3 is scarcely typical because of the more numerous radiating processes and the greater degree of fusion. Figure 2 (Pl. I) is atypical because of the unusual narrowness of the delicate flange. Figures 84 and 85 are poor pictures because too much was attempted by illuminating both background and spore surface. Normally, the flange is torn off to a greater or lesser extent, though, with careful handling and undermaceration, some complete specimens can be obtained.

Transition is complete from a type with extremely delicate flange with unfused, ctenate (comblike) processes to ones with elements terminally fused to form a rim, and to forms with a reticulate flange. The actual specific value of the flange type is unknown. This alliance includes species or varieties which are among the earliest of the triangulates, appearing even in the Eagle coal. One species, *T. radiatus* (Ibrahim) Schopf, Wilson, and Bentall, which will not be considered here separately, is of considerably later range, principally Allegheny, in the Appalachian coals. It may be that Figure 3 is of this type. The author has examined large quantities of some megaspores from the Michigan coal basin, including the *T. rotatus* material, but at present is unwilling to differentiate that species *sensu stricto* from gradational forms including *T. radiatus*.

T. praetextus ZERNDT (FIG. 20)

The coarse-featured spore in Figure 20 was described in the discussion of Plate I. The arcuate ridge is prominent but can scarcely be considered a flange. The diffuse pustules or stubby spines vary considerably in different specimens. The most common occurrence of this species is in the mid-Kanawha. The age of the European material is Upper Dinantian and Lower Namurian. Such a stratigraphic discrepancy may be one evidence of specific difference of the Appalachian material.

[23] Pp. 19–21, Pls. XIX, XXII, and XXIII of Part I (1934), of ftn. 19 (1937).

A variety shown in Figures 91–94 is considerably smaller; and the thinner, wavy, fringelike arcuate ridge may be interpreted as a very narrow, solid flange. The rays of the triradiate tetrad scar are prominent, ribbon-like, and irregularly fluted. This form somewhat resembles *T. hirsutus* but does not appear to be lageniculate. It is important in the Lower Kanawha coals.

T. clavatopilosus (WICHER) SCHOPF, WILSON, AND BENTALL (FIGS. 95–99)

The examination of spores of *T. clavatopilosus* is rendered difficult by the amount of extraneous residue which appears to be matted over the surface, together with the filiform appendages. It may be that the specimens shown are incomplete. The hairs seem to be short and appear indistinguishable from the rami of the lacerate flange. Spores such as this from the lower coals are difficult to recover in good condition. A study of them is aided by an examination of thin sections.

The spore shown in Figure 135, Plate IV, is possibly related. The trilete structure is nearly the same, i.e., very strong and leathery in appearance, with considerable apical development. The flange, however, is narrower and made up of more delicate protuberances.

Three additional species presumed to belong to the section Triangulati which are not shown on Plate III are discussed here to avoid discontinuity.

T. triangulatus ZERNDT (FIGS. 5 AND 112–14)

The general appearance of the spore is best shown by Figure 5, already discussed. It is one of the most common of all megaspores and has a range throughout the Middle and Upper Pennsylvanian. It may be considered typical for the section Triangulati. Schopf[24] has discussed this species in considerable detail. One spore feature, not mentioned in the preceding pages, is the presence of a network of thickenings (reticulation), which occurs on the wall of the spore body and is notable in this species. The reticulation of the distal surface is more prominent than that of the proximal half. Occasionally, a system of reticulation is to be found on the flange. There is a considerable range of size (300–800 μ) and ornamentation on specimens assigned to *T. triangulatus* which may be of specific rather than varietal quality. In the variety shown in Figure 111, the flange is thicker and perhaps wider, and the trilete rays are shorter.

T. artecollatus NOWAK AND ZERNDT (FIGS. 140–41)

Triletes artecollatus appears to be somewhat ambiguous. It may be more reasonably associated with the Auriculati. The spores shown here more closely resemble the figure given by Zerndt[25] for his Type 39 than they do the original description and figures.[26] They have a pustulose surface, weak trilete apparatus, and strong arcuate ridges. The surface of the pyramic area is almost "warty" near the apex. The much younger age (Allegheny) of this material than the original specimens (Dinantian) makes specific identification questionable.

T. gymnozonatus SCHOPF (FIG. 155)

The final species of the Triangulati discussed here is a small, unornamented, smooth, black megaspore. The arcuate

[24] Pp. 32–37 of ftn. 7.

[25] Fig. 11, p. 16, of ftn. 19 (1937).

[26] J. Nowak and Jan Zerndt, "Zur Tektonik des östlichsten Teils des polnischen Steinkohlenbeckens," *Acad. Polon. Sci. Lett. Bull. Internat.*, Ser. A (1936), p. 58, Pl. I, Figs. 4–5.

ridges are present but inconspicuous. It is identified with reasonable certainty, and the age of the specimens found is Upper Allegheny (Upper Freeport coal). Here again is a fortunate specific correlation between spores of approximately the same age in the Appalachian and eastern Interior coal basins. Megaspore floras of more coals from the Illinois Basin will have to be studied to determine the relative value of such spore correlations.

DISCUSSION OF THE GENUS *Triletes*, SECTION AURICULATI

The spores of the Auriculati are characterized by the radial development of lobes (auriculae) opposite the trilete rays. The flange is usually weakly developed at the periphery of the interradial areas.

T. appendiculatus MASLANKIEWICZOWA

The three-lobed character of spores of the group is inconspicuous in some species, but in this one, from the uppermost beds of the Kanawha or Lower Allegheny, the lobes are particularly prominent. An illustration of this interesting form was inadvertently omitted. It has auriculae which extend a distance of nearly one-half the radius of the spore beyond the spore body, and on these earlike flaps are short, sharp spines or tubercles. The spore body is granulose, and the trilete apparatus is very thick, with the rays tapering to sharp points. A gradational series from species of this sort to species with inconspicuous "ears" occurs.

T. auritus ZERNDT (FIGS. 7–9, 13–15, 151–52)

This species has been described in the earlier discussion of possible specific variations. It may be differentiated from its varietal forms only with difficulty. The variety *T. auritus grandis* Zerndt is presumed to be represented by the form with bulbose "ears" shown in Figures 4 and 5. Variety II (Figs. 147–50) may be favorably compared with *T. auritus* in the adjacent figures (Figs. 151–52). Such haptotypic features as flange and trilete apparatus are recognizably different in the two. The spores in this group are somewhat similar to some of those described as *T. silvanus*. The specimen of *T. silvanus* illustrated in Ibrahim's dissertation[27] probably is less conspicuously flanged, and the auriculae are smaller, but in the material illustrated by Wicher[28] as *Sporites silvanus* (Ibrahim), the flange and the auriculae are closely comparable to those of *T. auritus*.

Variety III (Fig. 156) and variety IV (Figs. 157–59) are poorly illustrated. They are about one-third the size of *T. auritus* and are smooth and densely black. The auriculae in variety IV are larger, and the flange or arcuate ridge is less conspicuous.

T. silvanus (IBRAHIM) SCHOPF, WILSON, AND BENTALL (FIGS. 142–46)

The species *T. silvanus* is somewhat similar to *T. auritus*, just described. The specimens illustrated are larger than the type material and perhaps should be specifically differentiated. The coat is usually granulose, though the proximal side is roughened in some specimens, and on the distal side it may be warty. The flange is a convoluted, leathery fringe coinciding with the equator. The pyramic area is divided by a strong trilete apparatus with high, wide, crenulated

[27] Ahmet Can Ibrahim, *Sporenformen des Aegirhorizonts des Ruhr-Reviers* (Private printing; Wurzburg: Konrad Triltsch, 1933), Pl. II, Fig. 22.

[28] Carl A. Wicher, "Sporenformen der Flammkohle des Ruhrgebietes," *Arb. Inst. f. Paläobot. u. Petrogr. d. Brennsteine*, Vol. IV (1934), Pl. VIII, Figs. 5–8.

lips. In general character the spore is coarse and usually about 2,000 μ in diameter. It occurs in the Monongahela series, relatively higher than the European specimens.

T. nigrozonales STACH AND ZERNDT (FIGS. 136–30)

The species *T. nigrozonales* is quite dark and smooth, with sharply defined haptotypic features. The flange is narrow and slightly crenulated. The auriculae are strongly developed. It appears to be distinct from a number of other Auriculati which occur with it in Lower Allegheny and Upper Kanawha beds. Its range is short and comes near the base of the short European range (Westphalian C).

DISCUSSION OF THE GENUS *Triletes*, SECTION LAGENICULA

The chief characteristic of the lageniculate group of *Triletes* is the remarkable development of the apical segments of the spore coat to form a vestibule. The resultant shape of the spores has been discussed. There are a number of forms which appear to be intermediate between these and some of the other spores already described. Schopf[29] discussed the difficulty of determining the affinity of spores to Lagenicula by the presence of the vestibule alone.

T. crassiaculeatus (ZERNDT) SCHOPF, WILSON, AND BENTALL (FIGS. 107–10)

The spores shown here may differ from the type material in several features, but no other specific characterization fits these as well. The vestibule is slender and small but well differentiated. The surface is sparsely spinose. The spore coat and surface resemble those features of *T. kidstoni*. It has been recognized only from some of the older coals of the Kanawha group.

T. hirsutus (?) (LOOSE) SCHOPF, WILSON, AND BENTALL (FIGS. 80–83)

This species is not positively identified. The material illustrated here is older than European specimens. The spore body, about 800 μ in diameter, somewhat resembles that of rotate spores, such as *T. radiatus*. The distal side is covered by an indument of cylindriform rami of varying lengths. Individual rami extending radially from the equator may be the sole remains of the lacerate type of broad flange.

T. levis (ZERNDT) SCHOPF, WILSON, AND BENTALL (FIG. 127)

Several spore types have been found which are tentatively considered to belong to this species and its varieties. The specific distinction of relatively unornamented Lageniculae is difficult. *Triletes levis* of the European fields is Stephanian in age. Varieties I and III (Figs. 126 and 130, respectively) have been found in the Waynesburg coal and some of the Lower Permian coals above, whereas the form here called *T. levis* and also *T. levis* var. II are found only in early Kanawha coals.

These spores have dense-black coats; thick, fleshy lips; and no evidence of arcuate ridges, flanges, or spines. The trilete apparatus is prominent, and the interradial plications are distinctive. The vestibule is prominent to inconspicuous in the different varieties. In Figure 127, *T. levis* actually looks very nearly like the much larger *T. simplex* in Figure 134.

Statistical analyses of additional material will probably result in a separation of some of the species based on early Kanawha forms from those of Upper Monongahela age.

[29] Pp. 27–28 of ftn. 7.

T. nudus (NOWAK AND ZERNDT) SCHOPF (FIGS. 100–104)

The five specimens shown in Figures 100–104 are all from the Waynesburg coal. This species has not been found in the younger seams of the Pottsville. The range of the type material is equivalent to Upper Mississippian and Pocahontas, as nearly as can be determined. Even with this discrepancy in age, the spores are indistinguishable on the basis of published descriptions and figures. If they are actually specifically different from the European material, criteria for so adjudging them are not recognized. Schopf has described some specimens from No. 6 coal of Illinois which may also be specifically distinct. The spores illustrated here show a well-defined arcuate ridge and very high vestibule, but no other surface appendages or emphytic ornamentation.

Very similar is *T. nudus* var. I, except that the arcuate ridge is inconspicuous and the spore in over-all appearance is gourd-shaped rather than bottle-shaped.

T. rugosus (LOOSE) SCHOPF (FIG. 105)

The figure is too small to reveal much of the nature of the spore. It has low, distinct lips; thick coat; rough, warty surface, with well-defined arcuate ridges and trilete apparatus. No vestibule is evident. Here again is a spore in the Upper Freeport coal which is approximately of the same age as the material found in the Illinois Basin.

T. translucens SCHOPF (FIGS. 115–16, 124)

Triletes translucens is somewhat similar in general character to *T. rugosus*. It has thinner walls and is usually smaller, although a disproportionate range in size is shown by comparing Figure 115 with Figure 116. These spores were carefully examined, and no significant differences other than size are apparent. The type shown in Figures 117–18 is recorded as a variety, but actually so little is determinable from the specimens found that it is of little value taxonomically and stratigraphically as it now stands. These spores can best be studied by transmitted light, whereas most of the preceding spores are examined principally by direct light.

Since no illustrations are given, no discussion of the other genera of megaspores will be undertaken at this time. No other genus has as many species as *Triletes*, but several species of each of several other genera have been found and are used for stratigraphic correlations.

DISCUSSION OF THE MICROSPORE ASSEMBLAGES

The microspores of the Appalachian coals have not been studied systematically. A total of fifty-eight species or varieties, however, are recorded from about twenty coal seams. Plate V shows fifteen different species in ten genera which are commonly found. All occur in three coal seams of southern West Virginia. These three seams—the Powellton, Campbell Creek, and Alma, all of mid-Kanawha age—are easily differentiated from one another in that area, on the basis of microspores. The Powellton shows an abundance of *Laevigato-sporites* (Figs. 174, 178) and *Lycospora* (Fig. 184). Very few other microspores occur. The Campbell Creek coal has a large number of microspores, including *Laevigato-sporites* and *Denso-sporites* (Figs. 177, 179), but it is particularly marked by several species of *Granulati-sporites* (Figs. 172, 173, 175). The Alma coal microspore flora is dominated by a certain species of *Denso-sporites*. Geographic variation of these floras is undetermined at this time. The identification of the material is impeded,

as it is in the case of the megaspores, by the confused status of the recorded species. Of the fifty-eight forms found, more than two-thirds appear to be new. From a preliminary analysis it appears that the microspores are more suitable than megaspores for distinguishing closely spaced coal seams and in identifying benches which may diverge from one another as splits.

MICROFOSSIL EVIDENCE FOR THE DIVISION OF THE PENNSYLVANIAN STRATA OF THE APPALACHIAN REGION

Examination of the microfossil flora in several geographically spaced samples from a single seam of coal shows, in many cases, a reasonable lateral variation of the species present. In most seams, however, a typical microfossil assemblage is identifiable for a major portion of the range. A detailed study is now being made of the floras present in five coal seams (Waynesburg, Uniontown, Pittsburgh, Chilton, and Campbell Creek). This should ultimately determine the reliability of typical spore assemblages and the amount of lateral variation which may be expected.

Evolutionary floral changes, which mark "breaks" in the geologic succession, are quite noticeable in studying the microfossils of successive beds. A conspicuous change appears in the flora above the Lower War Eagle coal, probably having occurred during the time of deposition of the Eagle shales and limestone. The floral assemblages of the subsequent coals (Cedar, Eagle, and others), up to the shales (including the Stockton limestone) above the Matewan coal, are rather uniform in the samples studied. The Powellton, Campbell Creek, Alma, and Cedar Grove coals, deposited in that order above the Matewan (?) shales, are remarkably uniform in megaspore assemblages. The prominently flanged spores of the Triangulati are most abundant and become progressively varied and specialized from the Powellton to the Cedar Grove. A marked change in the floras occurs somewhere in the interval before the deposition of the Hernshaw coal. The actual "break" may be explained by change of conditions represented by the Dingess shale and limestone series.

One of the biggest changes in the floras occurs between the Buffalo Creek coal and the later Coalburg. Even the admittedly sketchy distribution record given on the chart in Figure 2 shows a marked difference between the megaspores of these two coals. The principal relationship of the Coalburg megaspores to previous floras is found in a few vestiges of the highly specialized, flanged megaspores of the Triangulati. According to present knowledge, these include some of the most overspecialized types of that group. Succeeding coals show almost none of these forms.

In West Virginia the Upper Freeport coal is separated from the Lower Freeport coal by a conspicuous floristic change. The several Kittanning coals are similar to the Lower Freeport. A major break comes also in the Monongahela series at the thick Benwood and Arnoldsburg limestones, for the Uniontown-Waynesburg flora is quite unrelated to the general type of megaspore flora found in the Little Pittsburgh, Pittsburgh, Redstone, and Sewickley coals. A study of the Arnoldsburg and/or Lower Uniontown coals has not been made, so the actual time of this change cannot be delimited.

Such major floristic changes should be considered in dividing the Pennsylvanian

rock sequence of the Appalachian Basin. Considerable additional evidence from further studies is required to substantiate some breaks, but the microfossils, along with other available information, can be put to use at any time.

REMARKS

The writer is keenly aware of the possibility of using microfossil floras in the correlation of coal seams, for the determination of coal reserves, for the recognition of split seams and erosional or nondepositional unconformities, and as a means of reducing the expense of prospecting and proving an area by the usual methods. But it is a painful fact that the whole science of micropaleobotany has failed to meet its challenge, except for a few instances of local application of its principles. This failure, which need be only temporary, is principally attributable to the confused status of microfossil nomenclature and identification. As already stated, the present confusion stems from the difficulty of identification of material, from the uncertain status of many species, and, basically, from the relative difficulty of determining the actual specific value of the variations between one microfossil and another.

Many species have been created that are doubtless indistinguishable from other species described. Inadequate illustrations and incomplete or muddled descriptions occur commonly in the literature. It should again be recalled that the present work is *not* a taxonomic treatise, for in most cases the illustrations would be quite as inadequate as some already referred to in the literature of this field, and there is no intention of giving here the detailed scientific descriptions which will be necessary when a complete study is published. The use of a common, simple terminology by all workers, regardless of nationality, must be forthcoming if the science is to advance or ever be of economic value. The confused status at present must gradually be resolved by a systematic comparison of the type material of all conflicting and intergrading species. Description of species by the use of symbols or formulas is decried as an additional complication. The paper and space saved are relatively unimportant, and the time saving is questionable. Publication of descriptions using such abbreviations or other laboratory devices could be likened to the publication of the untranscribed shorthand notes of a secretary rather than to the intended word message. It is probable that systems can be worked out to use such short cuts in the individual laboratories, but a straightforward word description accompanied by adequate photographs and/or diagrammatic drawings will be most useful to all.

It is not deemed reasonable that any commercial laboratory be required to publish, or censured for not publishing, systematic works. The arbitrary numerical designations which have appeared in the literature are justifiable for the average laboratory technician to use, especially under the present status of taxonomic confusion. If taxonomic uncertainty is reduced or eliminated, most laboratories will favor using a binomial system of nomenclature established on biological principles.

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